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Geomorphology of the Green River in Dinosaur National Monument

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GEOMORPHOLOGY OF THE GREEN RIVER

IN DINOSAUR NATIONAL MONUMENT

by

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ABSTRACT

Geomorphology of the Green River in

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by

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Longitudinal profile, channel cross-section geometry, and depositional patterns of the Green River in its course through the eastern Uinta Mountains are each strongly influenced by river-level geology and tributary sediment delivery processes. We surveyed channel cross sections at 1-km intervals, mapped surficial geology, and measured size and characteristics of bed material in order to evaluate the geomorphic organization of the 70-km study reach. Canyon reaches that are of high gradient and narrow channel geometry are associated with the most resistant lithologies exposed at river level and the most frequent occurrences of tributary debris fans. Meandering reaches that are characterized by low gradient and wide channel geometry are associated with river-level lithology that is of moderate to low resistance and very low debris fan frequency. The channel is in contact with bedrock or talus along only 42 percent of the bank length in canyon reaches and there is an alluvial fill of at least 12 m that separates the channel bed from bedrock at three borehole sites. The influence of lithology primarily operates through the presence of resistant boulders in debris fans that are delivered by debris flows from steep tributaries.

The depositional settings created by debris fans consist of (1) channel-margin deposits in the backwater above the debris fan, (2) eddy bars in the zone of recirculating

flow below the constriction, and (3) expansion gravel bars in the expansion below the zone of recirculating flow. These fan-eddy complexes are the storage location of about 70 percent, by area, of all fine- and coarse-grained alluvium contained within the canyons above the low-water stage. Immediately adjacent meandering reaches contain an order of magnitude more alluvium by area but have no debris fan-created depositional settings.

This study also describes the flood-plain and terrace stratigraphy of the Green River in the eastern Uinta Mountains and changes due to the operations of Flaming Gorge Dam, upstream from the study area. These landforms are vertically aggrading deposits that are longitudinally correlative throughout the 65-km study reach. The suite of surfaces identified includes a terrace that is inundated by rare pre- or post-dam floods, an intermediate bench that is inundated by rare post-dam floods, and a post-dam flood plain that is inundated by the post-dam mean annual flood. Analysis of historical photographs in the study reach shows that both the intermediate bench and post-dam flood plain are landforms that were not present in any of the 6 years for which photographs were examined between 1871 and 1954. Photographic replications also show that gravel bars consisting of bare gravel in 1922 and earlier photographs are now covered by fine-grained alluvium and vegetation. Decreased gravel-bar mobility is indicated by estimates of critical and average boundary shear stress. Comprehensive surficial geologic mapping of the study area indicates that the bankfull channel has decreased in width by an average of about 20 percent.

(150 pages)

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Paul E. Grams

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CHAPTER 1

INTRODUCTION

One of the most unique characteristics of the Colorado Plateau region of the United States is the disparity between the orientation of major drainage patterns and the trends of dominant geologic features. The result is perhaps the most extensive network of canyon-bound rivers in the United States. The Green River, tributary to the Colorado River and one of the trunk streams of the region, alternately flows through deep bedrock gorges and broad alluvial basins as it flows south across the east-west trending structural and topographic axis of the eastern Uinta Mountains in Colorado and Utah.

The geomorphic organization of canyon-bound rivers is determined by (1) the characteristics of the bedrock into which the canyon has been eroded, (2) the characteristics and frequency of hillslope and tributary sediment delivery to the trunk stream, (3) the hydrology of the trunk stream, and (4) the characteristics and volume of the sediment load of the trunk stream. The first objective of this study is to examine the relative influence of these factors in determining channel geometry, longitudinal profile, and distribution of alluvial deposits.

Specifically, Chapter 2 describes how bedrock lithology and structure and tributary sediment delivery influence channel and flood plain geomorphology in the canyon and meandering reaches of the Green River in the eastern Uinta Mountains. The geomorphic organization of the stream is described by channel geometry, longitudinal profile, and patterns of alluvial deposition and erosion. Detailed surficial geologic maps of the river corridor, surveyed channel cross sections, bed-material measurements, and archived data were collected and analyzed for this study.

The relationship between fluvial landforms, the river channel, and hydrology is of long-standing interest to geomorphologists, and concepts such as bankfull discharge, effective discharge, and the active flood plain are dominant paradigms (Wolman and

Miller, 1960; Andrews, 1980). However, continuing geomorphic research about an ever-widening array of channel types (Nanson, 1986; Pizzuto, 1994) suggests that these paradigms must be reassessed within this broader context.

River channels in narrow canyons are one of those channel types where fluvial landform-channel relationships can be expected to deviate from the original active flood plain-effective discharge paradigm. Stage-to-discharge relations are steep, shear stresses at flood stage are very high, bed material is very coarse, and macroturbulance is significant (Baker, 1984). The abundance of coarse material suggests that landforms along canyon rivers should be insensitive to the kind of hydrologic changes that lead to disequilibrium along wider alluvial rivers. Thus, fluvial landform adjustability, essential to maintaining consistent flood plain-channel relationships, may not exist in canyon rivers.

Chapter 3 builds on the first section of this study by describing the history of channel adjustment that has occurred along the Green River in the eastern Uinta Mountains in the past century. Completion of Flaming Gorge Dam, about 60 km upstream from the study area, in 1963 severely altered the streamflow and sediment regimes of the Green River in the study area. The results of this study show that the bed and banks of the channel are made up of coarse- and fine-grained sediments, that both these channel elements are adjustable, that longitudinally correlative flood plain-like features exist, and that they occur at multiple elevations as a result of changes in hydrology and sediment transport.

CHAPTER 2

GEOMORPHOLOGY OF THE GREEN RIVER IN THE EASTERN UINTA MOUNTAINS, COLORADO AND UTAH

Introduction

Bedrock gorges and deep canyons are among Earth's most spectacular landscapes. Canyons are found on most continents and occur where major drainages cross topographic barriers. The geomorphic organization of canyon-bound rivers is determined by (1) the characteristics of the bedrock into which the canyon has been eroded, (2) the characteristics and frequency of hillslope and tributary sediment delivery to the trunk stream, (3) the hydrology of the trunk stream, and (4) the characteristics and volume of the sediment load of the trunk stream. The relative influence of these factors in determining channel geometry, longitudinal profile, and distribution of alluvial deposits has only been investigated in a few places, especially the 400-km long Grand Canyon in northern Arizona.

The purpose of this chapter is to describe the role that bedrock lithology and structure and tributary sediment delivery play in determining channel and flood plain geomorphology in the canyons of the Green River in the eastern Uinta Mountains of Colorado and Utah (Fig. 1). The geomorphic character of this stream is evaluated by examination of channel geometry, longitudinal profile, and patterns of alluvial deposition and erosion. The study area is located at the northern edge of the Colorado Plateau and includes a diverse assemblage of lithologies and geologic structures that influence the river's geomorphology. Data collected and analyzed for this study include detailed surficial geologic maps of the river corridor, surveyed channel cross sections, and bed-material measurements. The geomorphic organization of the Green River in the Uinta Mountains is compared to Grand Canyon and generalized to the Colorado Plateau.

Previous Work

Perhaps the most extensive canyons in the United States are found in the Colorado Plateau, a large region of uplifted sedimentary rocks. The disparity between the orientation of present stream courses and trends of dominant geologic structures causes the largest rivers of the region to traverse diverse geologic formations of varying erosional resistance. The streams have carved deep and narrow canyons through more-resistant formations, or they meander through broad basins and smaller parks across less-resistant formations (Harden, 1990; Hunt, 1969). John Wesley Powell (1875) cited the Green River as a typical example of an antecedent stream, a river that had carved deep canyons as mountains rose in the river's path. Subsequently, geologists questioned this theory and offered alternate explanations (Davis, 1897; Jefferson, 1897; Sears, 1924; Bradley, 1936; Hansen, 1960; Hunt, 1969). Hansen (1986) presented evidence supporting the explanation first proposed by Sears (1924) that the present course of the Green River was the result of superposition from a course established on Tertiary sediments that filled local basins. Entrenchment of the canyons began in late Miocene-early Pliocene time when the Green River drainage was diverted from an eastward-flowing course across the present day continental divide in Wyoming to a southward course across the eastern Uinta Mountains (Hansen, 1986). The Canyon of Lodore (hereafter informally referred to as Lodore Canyon) is about 5 my old and the incision of its gorge, 760 m deep, occurred at an average rate of 15 cm per thousand yr (Hansen, 1986).

Geologists have also been interested in how bedrock geology controls specific fluvial-morphological characteristics of modern streams within canyons. Powell (1875,

p. 234) anticipated dangerous reaches of river by observing the lithology of nearby rocks, noting that: "In softer strata we have a quiet river, in harder we find rapids and falls." The pool-drop pattern of the Green River was obvious to river travelers, yet was undocumented until a channel profile was surveyed during investigations between 1917 and 1922 (U.S. Geological Survey, 1924). Most subsequent studies have emphasized the importance of either (1) bedrock lithology and structure, (2) tributary processes, or (3) mainstem hydrology in determining the geomorphic organization of the large rivers of the Colorado Plateau.

Leopold (1969) measured some of the fundamental geomorphic characteristics of the Colorado River in Grand Canyon including water-surface and bed profile, channel width, and the location of rapids and gravel bars. He argued that the average longitudinal profile of the river is nearly straight when viewed at the canyon-length scale despite the pool-drop characteristic of short reaches. Leopold (1969) asserted that the average profile and the semi-regular spacing of rapids, gravel bars, and deep pools — analogous to the riffle-pool sequence observed in small streams — are indications that the river is in a state of quasi-equilibrium with respect to material transport and channel morphology. Thus, the slope of the channel is adjusted to rework and transport the delivered sediment, however coarse, and the occurrence of rapids and pools is an inherent characteristic of transport mechanics. Later, in an investigation encompassing several large rivers of the Colorado Plateau, Graf (1979) found that the spacing of rapids was essentially random, an indication that local conditions and not internal adjustment mechanisms determined rapid and pool location. Graf (1979) also determined that debris fans created most of the rapids he investigated, but did not explain the cause of every rapid. In contrast, Dolan and others (1978) and Howard and Dolan (1981) concluded that nearly all of the large rapids and deep pools in Grand Canyon are located at debris fans at the mouths of tributaries whose locations are determined by geologic structures such as major faults, folds, and fracture zones. Tributary processes are therefore highly important in determining the formation of debris fans and rapids, but geologic structure and geologic history are the ultimate controls, dictating where tributaries occur.

Canyon-bound rivers have systematic characteristics that are similar over long reaches. The relationship between channel geometry and bedrock lithology and structure is the basis for division of the Colorado River in Grand Canyon into morphologically similar reaches. Schmidt and Graf (1990) identified 11 reaches of similar bedrock resistance and similar channel geometry based on examination of channel cross sections surveyed at approximately 1.6-km intervals by Wilson (1986). Smith and Wiele (1995) statistically analyzed the same set of cross sections and demonstrated that the influence of geology on channel geometry is sufficiently strong that a "typical" cross section can be defined for reaches of similar river-level geology.

Although descriptions and classifications of fluvial bedforms are common (Church and Jones, 1982; Jackson, 1975), few schemes have specifically discussed bedforms in deep canyons. Baker (1984) described a classification of gravel bedforms in bedrock systems that emphasizes local control features, such as tributary fans, and the hydraulics of extreme floods. Howard and Dolan (1981) classified deposits in Grand Canyon based on grain size: (1) Bouldery debris fans that occur at the mouths of most tributary streams and are reworked by large floods on the Colorado River, (2) main-stem cobble bars transported only during floods, and (3) fine-grained alluvium deposited in eddies and along the channel margins and which are transported primarily as suspended load. These aspects of the fluvial geomorphic organization of canyon-bound rivers transcend local variations in lithology.

Schmidt and Graf (1990) and Schmidt (1990) focused on the details associated with depositional zones created by debris fans, and described patterns of alluvial sedimentation and erosion in eddies and channel-margin deposits. Within eddies, Schmidt (1990) distinguished between separation bars, formed near the point of flow separation, and reattachment bars, formed near the flow reattachment point. The sedimentology and stratigraphy of these bars have been described by Rubin and others (1990), Schmidt and Graf (1990), and Schmidt and others (1993). Schmidt and Rubin (1995) argued that the assemblage consisting of debris fan, upstream backwater, and downstream eddy and gravel bar comprises the fundamental geomorphic unit in canyons with debris fans and termed this unit the fan-eddy complex. For river systems on which debris fans are typical, patterns of sedimentation and erosion are largely determined by debris fan geometry, distribution, and ultimately, the frequency of fan-forming events. Sedimentology of debris fans, frequency of fan-forming debris flows, and the effects of debris fans on rapids were discussed by Webb and others (1989) and Melis and others (1993). The hydraulic characteristics of debris fan-created rapids and upstream pools were discussed by Kieffer (1985).

Geologic structure, tributary delivery processes, and mainstem hydrology all contribute to the geomorphic character of canyon rivers. Yet comprehensive examination of these channel-organizing elements, particularly in a system outside Grand Canyon, is lacking. Only the study of rapids by Graf (1979) addressed any of the geomorphic components of the canyons of the eastern Uinta Mountains; thus the applicability of Grand Canyon models has not been tested elsewhere.

Geological Setting and Description of Study Reach

The Uinta Mountains are a broad east-west trending arcuate anticline, separated in the middle by a structural and topographic low. The range spans parts of northeastern Utah, southwestern Wyoming, and northwestern Colorado. The eastern Uinta Mountains range in elevation from 2,960 m at the top of Diamond Peak to 1,448 m at the

Green River near the mouth of Split Mountain Canyon. Uplift and deformation of the Uinta Mountains began in latest Cretaceous time and continued into the Tertiary (Hansen, 1986). Bedrock exposures in the eastern Uinta Mountains range from highly resistant Precambrian core complexes to soft Tertiary sediments. Regionally, the rocks dip gently to the south-southwest (Hansen and others, 1983). Folds and faults cause large variations in dip over short distances. Table 1 summarizes the rock formations, the reaches over which they outcrop at river level, and their bedrock resistance class. Bedrock resistance was adapted from the classification of Harden (1990). This semi-quantitative classification ranks bedrock on a scale of 1 to 9 in order of increasing resistance to erosion.

Mapped faults in the eastern Uinta Mountains generally trend NW-SE and NE-SW (Hansen and others, 1983). Faulting occurred during the Laramide uplift and post-Laramide (middle to late Tertiary) extension. In addition to the mapped faults, Hansen and others (1983) showed an abundance of similarly trending joint sets. Nearly all of the major tributaries and many of the smaller drainages to the Green River in the north-south trending Lodore Canyon are aligned with these geologic structures. The largest tributaries such as Pot Creek, Zenobia Creek, and Jack Springs Draw run adjacent to mapped faults.

The Green River in the eastern Uinta Mountains is divided into six subreaches based on the distinction between canyon-bound and "park" reaches and were originally named by Powell (1875). These reaches have distinct meander patterns and relationships with geologic structures.

The river planform in the canyon reaches of Lodore Canyon, Whirlpool Canyon, and Split Mountain Canyon does not meander; the river tends to flow straight for about 2 to 4 km then bends abruptly entering another straight reach. Many of these bends, like tributary alignments, are coincident with geologic structures. In Split Mountain Canyon, for example (Fig. 1), the river cuts across the rock strata into the core of the anticline then turns 90 degrees west and flows along the structural axis for about 6.5 km, and then, just as abruptly, veers back across the structural trend and flows out of the anticline into the Uinta Basin. These reaches all contain debris fans and are called debris fan-dominated canyons consistent with the terminology of Schmidt and Rubin (1995).

Meandering reaches fall into two categories, restricted meanders and incised meanders. In the single bend through Echo Park, the channel and the valley meander at the same amplitude, characteristic of incised meanders. In the restricted meanders of Brown's Park and Island Park, the Green River flows through soft Tertiary and Mesozoic sediments in occasional contact with more resistant Paleozoic bedrock on the outsides of meander bends. The meander amplitude of the channel is less than that of the valley and only the outside margins of the meanders impinge on bedrock.

Hydrological Setting

The study reach consists of two hydrologically distinct segments, demarcated by the Yampa River confluence at Echo Park (Fig. 1). Flow is completely regulated by Flaming Gorge Dam for a distance of about 104 km upstream from Echo Park. A gaging station near Greendale, Utah (station number 09234500), immediately below the dam, measures flow for this reach. The typical pre-dam hydrograph was dominated by spring snowmelt-runoff and low fall and winter baseflows. The pre-dam mean annual flood was 334 m^3s^{-1} and has been reduced by about 63 percent to 139 m^3s^{-1} since dam closure (Fig. 2). The volume of total annual runoff and the mean annual discharge have not been affected by the operations of Flaming Gorge Dam (Andrews, 1986).

The unregulated Yampa River flows into the Green River at Echo Park. The mean annual flood of the Yampa River is unchanged for the period from 1920 to present and is similar to that of the Green River prior to construction of Flaming Gorge Dam

(Fig. 2). The combination of regulated and unregulated flow from the Green River and the Yampa River results in a 26 percent decrease in the mean annual flood at the gaging station near Jensen, Utah (station number 09261000), 46 km downstream from Echo Park.

Sediment transport has also been affected by closure of Flaming Gorge Dam. Sediment sources downstream from the dam are limited to the bed and banks of the river and ungaged tributaries upstream from the Yampa River. The largest tributaries, Red Creek and Vermillion Creek, enter the Green River 18 km and 70 km downstream from the dam, respectively. The only site with a long-term record of sediment transport near the study area is about 150 km downstream from the dam at the Jensen, Utah, gage. The mean annual load of suspended sediment has been reduced by about 54 percent at this site, from 6.28×10^6 Mg to 2.91×10^6 Mg (Andrews, 1986).

Methods

Channel Cross Sections

We measured 67 channel cross sections at approximately 1-km intervals to characterize channel geometry. These cross sections were surveyed in 1994 during low discharge using a geodetic total station and depth-recording echo sounder. Additional water surface elevations were surveyed at each cross section during peak flow in June and July 1995. Characteristics such as bed and bank material, high-water marks, bankfull stage indicators, and distinct geomorphic surfaces were noted and surveyed at each site. The precise location of each cross section was recorded on aerial photographs (1:5,000 scale) and topographic maps. Channel geometry characteristics at low and post-dam bankfull discharge were calculated from the survey data.

The bed material was determined at each cross section either while wading or by interpreting fathometer traces. Sand beds produce a smooth fathometer trace, sometimes showing ripples or dunes. A gravel bed produces an uneven fathometer trace indicative of coarse bed material. The fathometer trace of a boulder bed is even more irregular, often showing sudden changes in depth corresponding to individual boulders. The bed material coarsens from bank to thalweg at most cross sections. The bed material recorded for each cross section is the material that occupies > 50 percent of the bed in the channel thalweg.

Gravel and sand bars exposed at low water represent the only portion of the stream bed that is easily accessible. Bed material size was measured at 18 gravel bars; each bar was sampled at the upstream end below the high-water line. Particles were sampled at regularly spaced intervals along a tape measure for the above-water portion of the bar and by random walk for the submerged areas that were wadable (Wolman, 1954). Median diameter, lithology, and roundness were recorded for each particle. Roundness was visually estimated on a scale from angular to rounded.

The primary criteria for cross-section establishment were the desired 1-km spacing, the existence of uniform downstream flow, and feasibility of measurement. Cross sections were generally not surveyed in rapids or in large recirculating eddies. Because these areas were avoided, few cross sections traversed eddy-deposited sand bars, gravel bars in flow expansions, and coarse alluvium in rapids. Therefore, analysis of bed material distribution determined from cross-section data describe characteristics of uniform flow reaches. Our observations of bed material in rapids and eddies indicate that the thalweg is coarser in the unsurveyed areas.

Mapping of Surficial Geology

Surficial geology was interpreted on aerial photographs (1:5,000 scale) taken in 1993 during low discharge (33.4 m^3s^{-1} and 45.3 m^3s^{-1} above and below Echo Park, respectively). The preliminary maps were field checked then transferred to a 1:12,000 scale topographic base map using a reflecting projection table. A multilayered deposit classification strategy was devised to incorporate a maximum amount of information in a manageable format. Six geomorphic characteristics were specified for each mapped deposit or feature: (1) Bedrock exposure at river level, (2) reach in which each deposit is located (Lodore Canyon, Echo Park, Whirlpool Canyon, Island Park, or Split Mountain Canyon), (3) whether or not the deposit is located within a debris fan-eddy complex, (4) grain size, (5) depositional environment, and (6) elevation of the deposit in relation to the low-discharge water surface. Bedrock type at river level and reach were determined from geologic (Hansen and others, 1983) and topographic maps. Each discrete assemblage of debris fan, eddy bar, upper-pool deposit, and expansion bar was grouped and assigned a unique fan-eddy complex number. Completed maps were digitized into a geographic information system for areal analysis of deposits.

Inventory of Rapids and Riffles

The correlation between debris fans and rapids was evaluated by an inventory of all rapids and riffles on the Green River within the study reach. Our criteria were similar to that of Graf (1979) who defined a rapid as a location where "debris particles are numerous enough or large enough to break the water surface at mean annual discharge." We defined a rapid as any discrete river segment where breaking water was visible across most of the channel on the 1993 aerial photographs. The cause of the channel constriction and the material of each river bank were recorded for each rapid.

Results

Map Unit Descriptions

Deposit Material

Deposits were divided into four broad classes based on textural differences that could be clearly distinguished on aerial photographs. Figure 3 shows surficial geology of a typical reach in Lodore Canyon that has numerous debris fans and abundant coarse-grained alluvium. Fine-grained alluvium includes all alluvial sands, silts, and clays. Individual deposits may contain sedimentary structures or be massive. Thickness of fine-grained deposits can range from a few centimeters to several meters. Coarse-grained alluvium includes all pebble- to cobble-sized deposits from 2 to 256 mm median diameter. Deposits are moderately to well-sorted and contain rounded to sub-angular particles. A significant portion of the bank and bed material in the Green River canyons consists partly or entirely of coarse-grained alluvium. These include emergent mid- and side-channel gravel bars and reworked talus or debris. Many coarse-grained alluvial deposits are completely or partially covered by a veneer of fine-grained alluvium. These deposits are mapped as mixed fine- and coarse-grained alluvium (Fig. 3). Debris-fan material is poorly sorted, angular to sub-rounded and includes particles ranging in size from clay to boulders. Bedrock and talus includes rock outcrops and talus slopes. Talus is angular and dominated by large cobble and boulder sizes of local lithology. Bedrock and talus are not distinguished from one another because overlap of talus over bedrock is common.

Depositional Environment

Depositional environment describes the mechanism of fluvial deposition and is a classification independent of deposit material. Depositional environments were identified primarily by location, morphology, and bar stratigraphy. Deposit location and morphology were determined in the field and on aerial photographs. Stratigraphy was examined in the field at selected locations by excavating shallow trenches and was used to determine current direction during deposition.

Debris fans are accumulations of debris-flow deposited sediment located at the mouths of tributary streams (Fig. 3). Debris fan size, form, and composition are the products of tributary basin geology, debris-flow frequency, and debris-fan reworking by streamflow. Cutbanks created by the Green River and tributary streams show that debris fans are poorly sorted, matrix-supported diamictons with angular to sub-rounded, pebble to boulder-sized clasts; the matrix is clay to coarse sand.

Eddy bars form in zones of recirculating flow that occur downstream from channel constrictions. Figure 4 is a detailed map of a single fan-eddy complex in Lodore Canyon. Debris fans are the most common cause of channel constrictions, but talus slopes, bedrock outcrops, and gravel bars occasionally cause flow separation and eddy deposition. Although distinct separation and reattachment bars do occur in the canyons of the eastern Uinta Mountains, the eddy bar shown in Figure 4 is more typical. This bar extends the full length of the eddy, from separation to reattachment point; this distance is typically on the order of 1 to 3 channel widths. The area of fine-grained deposition is not limited to a secondary eddy cell, which is typical of separation bars, and the bar lacks a distinct return current channel, distinguishing it from a classic Grand Canyon reattachment bar. This lack of eddy bar differentiation within eddies resembles the tendency described by Schmidt and Rubin (1995) for separation and reattachment bars to appear merged under unregulated flow conditions where sediment transport rates are high. Excavations in undifferentiated eddy bars reveal upstream and onshore migrating dunes and climbing ripples, confirming deposition in a recirculating-flow environment. Reworking by wave action typically forms multiple river-parallel ridges and swales.

Expansion bars are generally about 1 to 3 channel widths in length and form in areas of flow expansion downstream from debris fan-created constrictions and associated expansions (Fig. 3). These deposits occur in association with eddy deposits and debris fans, but are located downstream from the eddy and in downstream-directed current. Expansion bars are predominantly gravel and often have a veneer of sand.

Channel-margin bars are narrow strips of alluvium that may be several channel-widths long and usually occur in straight reaches of relatively uniform downstream flow.

These deposits were also identified in Grand Canyon by Schmidt and Graf (1990). Internal stratigraphy is typically horizontally bedded but may include ripples or drift cross-stratification indicating downstream flow during deposition. River-parallel levees occur locally. The material of channel-margin bars is commonly sand but may include silt and clay. Box elder trees (*Acer negundo*) are common on high-elevation channel margin bars in the canyon reaches. Some channel-margin bars are located in the backwater immediately upstream from a channel constriction (Fig. 3 and Fig. 4). Point bars are channel-margin bars that are located on the inside of river bends in areas of decreased flow velocity but not in recirculating flow (Fig. 3).

Mid-channel bars are distinguished from other alluvial bars based primarily on size, shape, and location. They are typically several channel widths in length, lenticular or irregular in shape, and may occur either mid-channel or on channel margins. Mid-channel bars differ from expansion bars in that they do not typically occur in channel expansions below debris fan-created constrictions. Figure 5 is an oblique photograph that shows the abundant mid-channel bars of Island Park. Mid-channel bars that are located mid-stream are lower in elevation and are bare sand or covered by tamarisk (*Tamarix sp.*) or willow (*Salix sp.*). High-elevation mid-channel bars contain stands of mature cottonwood (*Populus fremontii*). Mid-channel bars typically occur in reaches of restricted meanders rather than in the fan-dominated canyons. Although vertical accretion is still an important process of bar formation, lateral accretion is evident by scroll-bar topography not displayed in the canyon deposits.

Distribution of Alluvium

Channel Bed and Bank Material

Channel bed material and bank material are two fundamental geomorphic characteristics of any stream. It is especially important to distinguish between bed and bank material in a canyon-bound river that may flow between banks of bedrock on an alluvial bed. The surficial geologic maps made for this study show the bank material along 160 km of river bank length for 60 km of channel centerline distance (Table2). These data show that in canyon reaches, bedrock and talus are the dominant bank materials, occurring along about 42 percent of the total length. Fine-grained alluvium is next in abundance, occurring along about 30 percent of the bank length. An additional 14 percent is debris-fan material, 11 percent is gravel, and 4 percent is mixed alluvium. Conversely, fine-grained alluvium is the dominant material in meandering reaches, occurring along 72 percent of the bank length.

Bed material at the surveyed cross sections, which represent the portion of the bed exposed at low discharge, and bore-hole data indicate that within the study area the river does not flow directly on bedrock. Fine-grained alluvium is the dominant bed material at 39 percent of the 67 surveyed channel cross sections in the study reach, and gravel is most abundant at 33 percent of the cross sections. A mixture of fine-grained alluvium and gravel covers 25 percent of the cross sections and the remaining 3 percent have boulder and talus beds (Table 2). Fine-grained alluvium is more abundant in the meandering reaches and less abundant in the canyon reaches (Table 2). Despite the abundance of bedrock and talus on the banks, rarely is the bed comprised of these materials.

Bore-hole data indicate that the channel consists of river-deposited alluvium inset into the bedrock gorge. Drill holes completed for dam-site surveys at the entrance to Lodore Canyon (Wooley, 1930) and in Whirlpool Canyon (Merriman, 1941) show about 45 m of sand and gravel overlying bedrock. The dam-site survey above the mouth of Split Mountain Canyon shows 12 m of alluvium over bedrock (Merriman, 1940). The measured depths to bedrock are shown on the longitudinal profile in Figure 6. Individual rocks photographed in 1871 are still present in the same locations at river level (Stephens and Shoemaker, 1987), indicating there has been no significant shift in mean bed elevation during the past century. The cross-section data and the bore-hole data support the observation that nowhere does the bed of the river flow in contact with bedrock despite the occurrence of bedrock as bank material.

Coarse-Grained Alluvium

Debris fans are most abundant in the canyon reaches. The total number of fans, fan frequency, and average debris fan area are listed for each reach in Table 3. The canyon reaches have an average debris-fan frequency of 3.1 fans per km compared to 0.4 fans per km in non-canyon reaches. Debris fan frequency is similar in all the canyon reaches, but is highest in Whirlpool Canyon. However, the fans in Whirlpool Canyon are on average about one-half the size of fans in Lodore Canyon and Split Mountain Canyon.

One hundred one mapped deposits in Lodore Canyon are gravel or a combination of fine sediment and gravel (Table 3). The rest of the canyon reaches contain an additional 91 gravel deposits. The proportion of the total area of all alluvium in the canyons that is gravel varies from 38 percent in Lodore Canyon to 73 percent in Split Mountain Canyon. In the non-canyon reaches, about 35 percent of the area of all alluvium consists either completely or partially of gravel. Most of the exposed gravel in all reaches occurs as mid-channel and expansion gravel bars.

The downstream variation of bed material sizes within the study area was compared with estimates of reach average boundary shear stress. Shear stress was estimated from the product of the specific weight of water γ, the hydraulic radius R and the water-surface slope S,

$$\tau = \gamma RS. \tag{1}$$

Even in the relatively deep and narrow channel in the canyon reaches, R is well approximated by mean depth (cross-sectional area divided by channel top width). The shear stress was calculated for the stage that inundates the most prominent geomorphic surface in the canyon and meandering reaches. This is a broad terrace with mature cottonwood trees in the meandering reaches and a narrow but distinct terrace with box elder trees in the canyons. Figure 7 is a typical cross section in Lodore Canyon that shows this prominent terrace as well as the post-dam bankfull stage and corresponding flood plain. This prominent terrace was chosen because the post-dam bankfull-flow surface is much lower and not representative of the unregulated flow regime to which the gravel bars are presumably adjusted. Photographs taken during extreme events indicate that the prominent terrace is inundated by flows of about a 25-yr recurrence interval in the pre-dam flow regime. Because this stage did not occur during our study, we used the U.S. Geological Survey (1924) water surface profile to estimate reach average slope at each cross section. Boundary shear stress was compared with estimates of critical shear stress for median particle size of each gravel bar. A first-order approximation of flows necessary to mobilize the gravel bars was made by estimating critical shear stress using the Shields relation (Shields, 1936),

$$\tau_{c50} = \tau^*_{c50}(\gamma_s - \gamma_f)D_{50}, \tag{2}$$

where τ_{c50} is the critical shear stress in Nm^{-2}, τ^*_{c50} is the critical dimensionless shear stress for the median particle diameter of the bed surface, γ_s is the specific weight of the solid in Nm^{-3}, γ_f is the specific weight of water in Nm^{-3}, and D_{50} is the median particle diameter of each sampled bar, in m. Values for τ^*_{c50} have been found to range over an order of magnitude and are affected by the bed-material size distribution (Andrews, 1983). For this approximation we used 0.033, the value found by Andrews (1983) to be the most common for coarse-bedded streams.

Figure 8 shows the downstream variation in critical shear stress necessary to entrain the median particle size of each gravel bar and the estimated reach average boundary shear stress at each cross section. The average boundary shear stress and the critical shear stress are larger in canyon reaches than in meandering reaches. The calculated shear stresses for the pre-dam 10-yr flood approximate and sometimes exceed the estimates for critical shear stress in both canyon and meandering reaches.

Fine-Grained Alluvium

Fine-grained alluvium is abundant in the canyons of the Green River in spite of the river's high gradient, high average boundary shear stresses, and narrow alluvial valley because of the high frequency of fan-eddy depositional environments. The wide alluvial bottoms of meandering reaches, however, contain an order of magnitude more alluvium in areal exposure than the canyon reaches. Between 66 and 94 percent of all alluvium exposed at low discharge in canyon reaches is at least partially composed of fine-grained material (Table 3). Although the thalweg of the channel is dominated by coarse material in the canyons, fine-grained material occurs at 60 percent of the cross sections.

Fan-Eddy Complexes

In the canyon reaches, fan-eddy complexes are common and are the dominant storage location of fine- and coarse-grained alluvium. For example, the constriction in the fan-eddy complex shown in Figure 4 is created by a debris fan formed at the mouth of a tributary entering from the south side of the canyon. Channel-margin deposits occur on both sides of the channel in the backwater above the constriction. A large eddy bar, 150 m long, mantles the downstream edge of the debris fan and extends the full length of the eddy at bankfull flow. The gravel bar is located downstream from the eddy where downstream flow occurs across the full width of the channel during bankfull flow. Although there is variation in the size and characteristics of individual debris fans, eddy bars, and gravel bars, each of these elements is present in most fan-eddy complexes. Another fan-eddy complex at Rkm 558.3 in Lodore Canyon is shown in an aerial photograph (Fig. 9). This debris fan constricts the channel and forms a small rapid. The eddy bar mantles the downstream edge of the fan and is a typical separation bar. The large downstream expansion gravel bar is attached to the left bank and is covered by a veneer of sand. While most of our data and discussion focus on the plan-view characteristics and distribution of the fan-eddy complex, these complexes are in fact three-dimensional forms. Pools are present above and below the constriction, increasing depth by a factor of two to three (Fig. 10). At the constriction, depth is reduced by a similar magnitude. Gravel bars are located below the lower pool and thalweg depth decreases.

There are 96 fan-eddy complexes in the mapped area. Not all debris fans create a fan-eddy complex; 79 percent of all fans in the mapped reach create a constriction that forms a fan-eddy complex. However, there are nearly twice as many debris fans as fan-eddy complexes because some fan-eddy complexes are formed by a debris fan on each bank; this often occurs where a structural control, such as a fault, crosses the river. The frequency of fan-eddy complexes ranges from 1.6 per km in Lodore Canyon to 2.3 per km in Whirlpool Canyon. In Lodore Canyon, 59 percent of all fine-grained alluvium and 74 percent of all gravel are stored in the fan-eddy complexes (Table 3). Eddy-deposited sand bars contain about 42 percent by area of all fine-grained alluvium in the canyon reaches and less than one percent in the meandering reaches (Table 3).

Comparison of gravel and boulder lithologies between debris fans and expansion gravel bars within individual fan-eddy complexes indicates that the debris fan is the primary source of the material for the gravel bar immediately downstream. Debris fan boulders are composed of lithologies from the contributing tributary basin, dominated by the most resistant lithologies found in that basin. For example, the debris fan at Rkm 563.6 (Fig. 4) is dominated by Uinta Mountain Group quartzite (70 percent) and shale (25 percent), Lodore Formation sandstone (5 percent), and rare cobbles of Madison Limestone. The expansion gravel bar immediately downstream has a similar ratio of lithologies with the more resistant formations more prevalent than the less-resistant shale (Table 4). The outcrop of Madison Limestone is much larger and the outcrop of Uinta Mountain Group shale is much reduced 1.5 km further downstream in the tributary basin that contributes to the debris fan at Triplet Falls; these differences are reflected in the composition of the downstream expansion gravel bar (Table 4). The sandstone and limestone cobbles in these bars must be derived entirely from the immediately adjacent upstream basins, because they are the upstream-most tributary basins in Lodore Canyon to contain outcrops of these rocks.

Longitudinal Profile

The stair-stepped longitudinal profile of the Green River (Fig. 6) is related to variations in lithology and debris fan occurrence. The average slope of the Green River is 0.0021 in the canyon reaches and 0.0008 in the meandering reaches (Table 5). The bedrock resistance along each reach at river level is also indicated on Figure 6. The rocks of highest resistance class are coincident with the reaches of steepest average gradient. Reach average gradient (5-km moving average) is plotted against bedrock resistance at each cross section in Figure 11a. The steepest reaches always occur in highly resistant rock, but low-gradient reaches occur in rock of all degrees of resistance. The same data are shown as weighted averages for individual canyon and meandering reaches in Figure 11b. In Lodore and Whirlpool Canyons, the Uinta Mountain Group quartzite lines the channel in the steepest reaches and the Paleozoic formations (except

Weber Sandstone) are associated with reaches of intermediate gradient. In Split Mountain Canyon, however, the Paleozoic rocks are associated with gradients steeper than occur elsewhere in any of the canyons, even those of more resistant formations. The Weber Sandstone, Mesozoic rocks, and Tertiary rocks of the park reaches are all associated with low channel gradients. Thus slope seems to be more closely related to bedrock resistance on a reach-average scale than on a per km basis.

The coincidence of debris fans and high-gradient reaches is also shown on Figure 6. Debris fan frequency is plotted against channel gradient in Figure 12. High debris-fan frequency is exhibited in all high-gradient reaches, and fan frequency is low in all low-gradient reaches.

Channel Geometry

Channel geometry is similar for reaches of similar geology. The ratio of channel width to channel depth at post-Flaming Gorge Dam bankfull discharge (122 m^3s^{-1} above the Yampa River confluence and 480 m^3s^{-1} below the confluence) is shown in Figure 13. The reach-averaged geometric parameters of channel top width, cross-sectional area, and width-to-depth ratio are all less in the canyons than in the meandering reaches (Table 5). The coefficients of variation are large for most parameters. This variation arises from local variations in channel characteristics. Despite this local variability, reach-length trends are evident. Moreover, the coefficients of variation decrease when the sampled subset for each parameter is stratified to include only geologically similar reaches (Table 5). This supports the designation of the selected reaches on criteria of bedrock geology as well as physiography.

The ratio of alluvial valley width to bankfull-channel width differs between canyon and meandering reaches. These ratios are higher for the meandering reaches than the canyon reaches (Table 5). The inverse relation between bedrock resistance and alluvial valley width is shown in Figure 14. Note that the coefficients of variation are higher in the meandering reaches (except Echo Park) than in the canyons. This is a result of the large variation in proximity of bedrock to the active channel in most meander reaches.

Spatial Distribution of Rapids

The rapids on the Green River through the eastern Uinta Mountains are formed where streamflow is constricted by coarse material impinging on the channel from one or both banks. We inventoried 95 rapids and riffles from aerial photographs, 45 percent more than Graf (1979) identified in the same reach using published river guides (Evans and Belknap, 1973; Hayes and Simmons, 1973). Of the 95 rapids identified, 76 percent (Table 6) are constricted by tributary fans, and 24 percent are constricted only by the expansion gravel bars just downstream from debris fans. The percentage of rapids constricted by debris fans includes some rapids that are impinged on the opposite bank by a gravel bar. Rockfall or a bedrock wall are frequently found on one bank at a rapid or riffle, but never on both banks; a debris fan or gravel bar is present at all constrictions. A majority of debris fans create rapids or riffles. One hundred ten debris fans were tallied on aerial photographs in the study area, 73 percent of these are co-located with rapids. Thus while all rapids are formed by constrictions that are caused by debris fans or downstream gravel bars, not all debris fans are associated with a rapid.

Discussion

The steep gradient and low ratio of channel width-to-depth in the debris fan-dominated canyons of the eastern Uinta Mountains are associated with both lithologic resistance and debris-fan frequency. Because river does not flow directly over bedrock and less than 50 percent of the bank is composed of bedrock or talus, it appears that bedrock does not have a direct influence on channel geometry and slope. However, because the detailed profile of the alluvium-bedrock interface is not known, the possibility remains that the present longitudinal profile is inherited from the profile established when the river did flow in contact with bedrock. Maintenance of an inherited profile would occur only if the river had aggraded the same amount everywhere. An adjusted profile would exist if differential aggradation had occurred; borehole data show that depth to bedrock and therefore aggradation since the river flowed in contact with bedrock are not the same throughout all the canyons. Aggradation may have occurred in response to a change in mainstem hydrology following deglaciation of the surrounding mountains or a change in tributary sediment delivery by debris flows. Moreover, the observed relation between debris fans and slope indicates that steep-gradient reaches are related to high debris-fan frequency. As sediment accumulated in the canyons, slope increased until streamflow competence matched the characteristics of tributary supply. The gravel bars with the largest mean particle sizes occur in the reaches of highest flood-flow average boundary shear stress.

Reworking of gravel bars and downstream transport of coarse-grained alluvium probably occurs only during floods on the order of the preregulation 25-yr recurrence interval. Observations of lithologies contained in gravel bars support the conclusion that gravel is rarely transported through the study reach under either the current regulated streamflow regime or the historic unregulated streamflow regime. The lithologic composition of gravel bars should reflect the distribution of lithologies of all upstream debris-contributing tributaries, not just the nearest upstream tributary basin if gravel was being transported through the canyons. Our limited investigation of lithologies contained in two debris fan/gravel bar pairs indicates that gravel bars are, in fact, dominated by the resistant lithology most abundant in the tributary basin immediately upstream. If attrition were the dominant process, we would expect to find a downstream fining of lithologies that did not occur. Thus in the debris fan-dominated canyons where deposition is determined by local fan-eddy complex depositional environments, sorting is determined by local hydraulic processes and possibly local attrition (from debris fan to gravel bar) rather than downstream hydraulic sorting and attrition.

Like other debris fan-dominated canyons of the Colorado Plateau (Schmidt and Rubin, 1995), fan-eddy complexes are the fundamental channel-organizing unit on the Green River in the canyons of the eastern Uinta Mountains. More than 60 percent of all fine- and coarse-grained alluvium is stored within these depositional units either as eddy bars, channel-margin deposits in backwaters, or expansion bars. This is in contrast to the meandering reaches, which store more than an order of magnitude more alluvium per km and have no fan-eddy complexes.

The geomorphic organization of the Green River in the eastern Uinta Mountains is essentially similar to that of the Colorado River in Grand Canyon as described by Howard and Dolan (1981), Schmidt and Graf (1990), and Schmidt and Rubin (1995). In both systems, channel geometry and gradient is associated with the lithology exposed at river level. Debris fan frequency is higher in the eastern Uinta Mountains; there are 3.3 fans per km on average in the eastern Uinta Mountains but fans are never more frequent than 2.9 fans per km in Grand Canyon (Schmidt and Leschin, 1995). Nevertheless, debris fans have a strong influence on sedimentation patterns in both systems. About 70 percent of all mainstem alluvium in the study area is contained within fan-eddy complexes, either in eddy bars, expansion bars, or channel-margin deposits in the backwater. The percentage of fine-grained alluvium contained in eddy bars is somewhat less, and is between 34 and 63 percent in the canyon reaches. Schmidt and Rubin (1995) showed that this percent varied between 44 and 75 percent in Grand Canyon and between 1 and 29 percent elsewhere on the Green River.

The largest difference between eddy bars in the Green River and Grand Canyon systems is the lack of differentiation between separation and reattachment bars in the eastern Uinta Mountains. This may be an indication of the relative abundance of fine-grained sediment with respect to the current streamflow regime. This is consistent with the observation made by Schmidt and Rubin (1995) that, prior to the closure of Glen Canyon Dam, many eddies in Grand Canyon were filled with sand, and separation and reattachment bars were merged.

The spacing of rapids is not regular, but is controlled by debris fans in both canyon systems. Other major channel elements such as gravel bars, sand bars, and pools are located in association with debris fans. Tributary basin geology and hydrology, which determine debris fan size and location, strongly influence mainstem channel morphology. Deposits such as sand and gravel bars found in each specific fan-eddy complex create a quasi-adjustable, self-formed alluvial channel inset within the bedrock/talus canyon.

Conclusions

The basic geomorphic characteristics of streams in canyons with debris fans are determined by the tributary sediment delivery processes. Longitudinal profile, channel geometry, and the occurrence of rapids in the canyons of the eastern Uinta Mountains are each strongly influenced by tributary-fan frequency. Bankfull channel width-to-depth ratio is lowest and gradient is steepest in the reaches with highest fan frequency; and all rapids are caused by debris fans or the gravel bars below debris fans composed of reworked debris-fan material.

Expansion gravel bars are the other element of coarse-grained alluvial deposits in debris fan-dominated canyons. These bars are located in the expansion downstream from debris fan-created eddies where uniform downstream flow resumes. The lithology of gravels in these bars indicates that their source is the debris fan immediately upstream and its associated tributary basin. This is an indication that the process of local sorting outweighs downstream sorting in these canyons. Estimates of average boundary shear stress for high flows and critical shear stress of gravel bars show that the channel gradient and bar-material size are in approximate adjustment with pre-dam flood conditions in both the canyon and meandering reaches of the study reach. Although the river flows alternately through reaches of extremely different geomorphic character, both are in a quasi-equilibrium condition.

Between 60 and 85 percent of the surface area of the alluvium in the canyon bottom exposed at low flow is contained in the depositional unit called the fan-eddy complex. More specifically, about 42 percent of all fine-grained alluvium in the canyons is stored in eddy bars within fan-eddy complexes. However, most of the total area of alluvium is contained in the meandering reaches where fan-eddy complexes are less important.

The fan-eddy complexes of the Green River in the eastern Uinta Mountains are similar to those described on the Colorado River in Grand Canyon by Schmidt and Rubin (1995). Approximately the same areal proportion of fine-grained alluvium is stored as eddy bars within these depositional units in both systems. In the eastern Uinta Mountains, however, there is less distinction between eddy-bar types; separation and reattachment bars are often merged.

TABLE 1. LENGTH OF GEOMORPHIC AND LITHOLOGIC SUBREACHES WITHIN STUDY AREA SHOWING THE BEDROCK RESISTANCE CLASSIFICATION FOR EACH FORMATION

Reach	Rock type at river level	Upstream end of reach (Rkm)*	Reach length (km)	Bedrock resistance class†
Lodore Canyon	Uinta Mtn. Group	579.5	22.7	9
	Lodore Formation	556.8	2.4	8
	Madison Limestone	554.4	1.4	8
	Paleozoic undif.	553.0	0.3	7.5
	Weber Sandstone	552.7	1.6	6
Echo Park	Weber Sandstone	551.0	3.2	6
Whirlpool Canyon	Paleozoic undif.	547.8	0.5	7.5
	Uinta Mtn. Group	547.3	2.4	9
	Lodore Formation	544.9	5.2	8
	Madison Limestone	539.8	4.3	8
	Paleozoic undif.	535.4	1.8	7.5
Island Park	Mesozoic undif.	533.7	11.6	3-5
Split Mountain Canyon	Paleozoic undif.	522.1	4.0	7.5
	Madison Limestone	518.0	3.4	8
	Paleozoic undif.	514.7	2.1	7.5
	Weber Sandstone	512.6	2.4	6

* Distances are in kilometers upstream from Colorado River confluence.

† Adapted from Harden, 1990.

TABLE 2. ABUNDANCE OF STREAM BANK MATERIAL AND BED MATERIAL FOR EACH GEOMORPHIC SUBREACH. BANK MATERIAL DETERMINED BY GIS ANALYSIS OF SURFICIAL GEOLOGIC MAPS MADE FOR THIS STUDY. BED MATERIAL DETERMINED FROM SURVEYED CHANNEL CROSS SECTIONS. FINE-GRAINED ALLUVIUM INCLUDES ALL SAND, SILT, AND CLAY

Parameter measured	Lodore Canyon	Echo Park	Whirlpool Canyon	Island Park	Split Mountain Canyon	Canyons	Meanders	Study Area
Length of bank (m)	41,468	10,010	16,702	32,941	9,977	68,147	42,951	111,098
	Percent of indicated material on bank*							
Gravel	5.2	6.4	18.9	6.4	19.0	11.1	6.4	9.7
Fine-grained	39.6	61.6	18.4	74.2	12.9	29.7	71.5	42.2
Mixed fine-grained and gravel	3.6	24.9	3.3	4.5	3.9	3.6	8.9	5.2
Debris	13.2	2.3	11.0	0.4	23.6	14.1	0.8	10.1
Bedrock and/or talus	38.5	4.8	48.3	14.5	40.7	41.6	12.4	32.9
	Percent of indicated material on bed†							
Gravel	40	0	25	54	0	33	32	33
Fine-grained	27	67	25	46	33	27	64	39
Mixed fine-grained and gravel	27	33	50	0	67	36	5	25
Boulders/talus	7	0	0	0	0	4	0	3

* Tabulated from surficial geologic maps.

† Tabulated from surveyed channel cross sections.

TABLE 3. DISTRIBUTION OF ALLUVIAL DEPOSITS BY REACH, DETERMINED FROM SURFICIAL GEOLOGIC MAPS

Geomorphic Characteristic		Lodore Canyon	Echo Park	Whirlpool Canyon	Island Park	Split Mountain	Canyons	Meanders	Study Area
Reach length (km)*		28.5	3.2	14.2	11.6	8.0	50.6	14.8	65.4
Area of alluvium (m^2/km)		34,962	323,366	30,008	769,943	33,164	33,319	675,688	175,947
Rapids (count)		53	0	26	2	12	91	2	93
Rapid frequency (count/km)		1.9	0.0	1.8	0.2	1.0	1.8	0.1	1.4
Debris fans (count)		81	1	53	5	35	169	6	175
Fan frequency (count/km)		2.8	0.3	3.7	0.4	2.9	3.3	0.4	2.7
Total area of debris fans (m^2)		739,543	5,598	259,407	13,520	281,211	1,280,161	19,118	1,299,279
Average area of fans (m^2)		9,130	5,598	4,894	2,704	8,035	7,575	3,186	7,424
Percent of	gravel	6	23	32	32	32	16	31	29
deposits by	fine-grained	62	65	55	67	27	55	67	66
area	mixed	32	12	13	1	41	29	2	5
Percent of	gravel	80	0	85	0	100	89	0	7
deposits in	fine-grained	51	2	89	0	100	64	0	8
fan-eddy	mixed	72	0	68	0	100	78	0	58
complex	all alluvium	60	1	85	0	100	72	0	10
Percent of fine-grained material in eddy bars		34	1	63	0	44	42	0	5

* Length of mapped reach (8 km of 11.9-km long Split Mountain Canyon were mapped).

TABLE 4. GRAVEL BAR PARTICLE SIZE AND LITHOLOGY

Site	Rkm 563.6*	Triplet Falls†
Location (Rkm)	563.6	562.6
D 50 (mm)	115	130
Percent of indicated lithology		
Uinta Quartzite	86	65
Uinta Shale	4	0
Lodore Sandstone	8	3
Madison Limestone	2	32

* Drainage basin has small outcrop of Madison Limestone and Uinta Group shale.

† Drainage basin has large outcrop of Madison Limestone and no Uinta Group shale.

TABLE 5. REACH AVERAGE CHANNEL GEOMETRY AT BANKFULL DISCHARGE AND REACH AVERAGE SLOPE (U.S. GEOLOGICAL SURVEY, 1924). CHANNEL GEOMETRY CALCULATED FROM SURVEYED CHANNEL CROSS SECTIONS

Geomorphic Characteristic	Browns Park	Lodore Canyon	Echo Park	Whirlpool Canyon	Island Park	Split Mountain†	Canyons	Meanders	Study Area
Reach length (km)*	3.6	28.5	3.2	14.2	11.6	11.9	54.6	14.8	69.4
Reach average slope	0.00039	0.00294	0.0006	0.002259	0.0007	0.00371	0.002143	0.00075	0.00177
Alluvial valley width (m)	819	95	246	108	721	134	101	674	285
CV§	0.61	0.25	0.33	0.34	0.51	0.43	0.31	0.63	1.31
Channel width (m)	139	60	176	80	172	81	66	147	100
CV	0.38	0.24	0.20	0.18	0.40	0.11	0.25	0.48	0.61
Cross-sectional area (m^2)	215.8	115.9	406.1	223.2	365.4	183.8	147.0	316.0	209.7
CV	0.40	0.27	0.22	0.17	0.46	0.16	0.39	0.53	0.65
Mean depth# (m)	1.6	2.0	2.3	2.9	2.2	2.3	2.2	2.2	2.2
CV	0.15	0.24	0.19	0.27	0.34	0.21	0.30	0.28	0.32
W/D ratio	90.5	34.1	78.2	30.0	89.9	37.0	33.3	74.7	52.7
CV	0.39	0.58	0.28	0.37	0.56	0.27	0.52	0.62	0.74
Valley W/channel W	5.9	1.6	1.4	1.4	4.2	1.7	1.5	4.6	2.9

* Length of reach in which surveyed cross sections are located.

† Surveyed cross sections include 2.5 km of Split Mountain Canyon.

§ Coefficient of variation (standard deviation / mean) for preceding parameter.

\# Cross-sectional area divided by channel width.

TABLE 6. CHANNEL CONSTRICTING FEATURE RESPONSIBLE FOR THE FORMATION OF RAPIDS, BY GEOMORPHIC SUBREACH. DATA COLLECTED FROM 1:5000 SCALE AERIAL PHOTOGRAPHS TAKEN DURING LOW DISCHARGE

	Lodore		Whirlpool		Split Mountain		All canyons	
Cause of Rapid	count	percent	count	percent	count	percent	count	percent
Debris fan only	35	66	19	73	12	75	66	70
DF - GB pair*	4	8	1	4	1	6	6	6
Gravel bar only	14	26	6	23	3	19	23	24
Totals	53	100	26	100	16	100	95	100

* Debris fan/gravel bar pair.

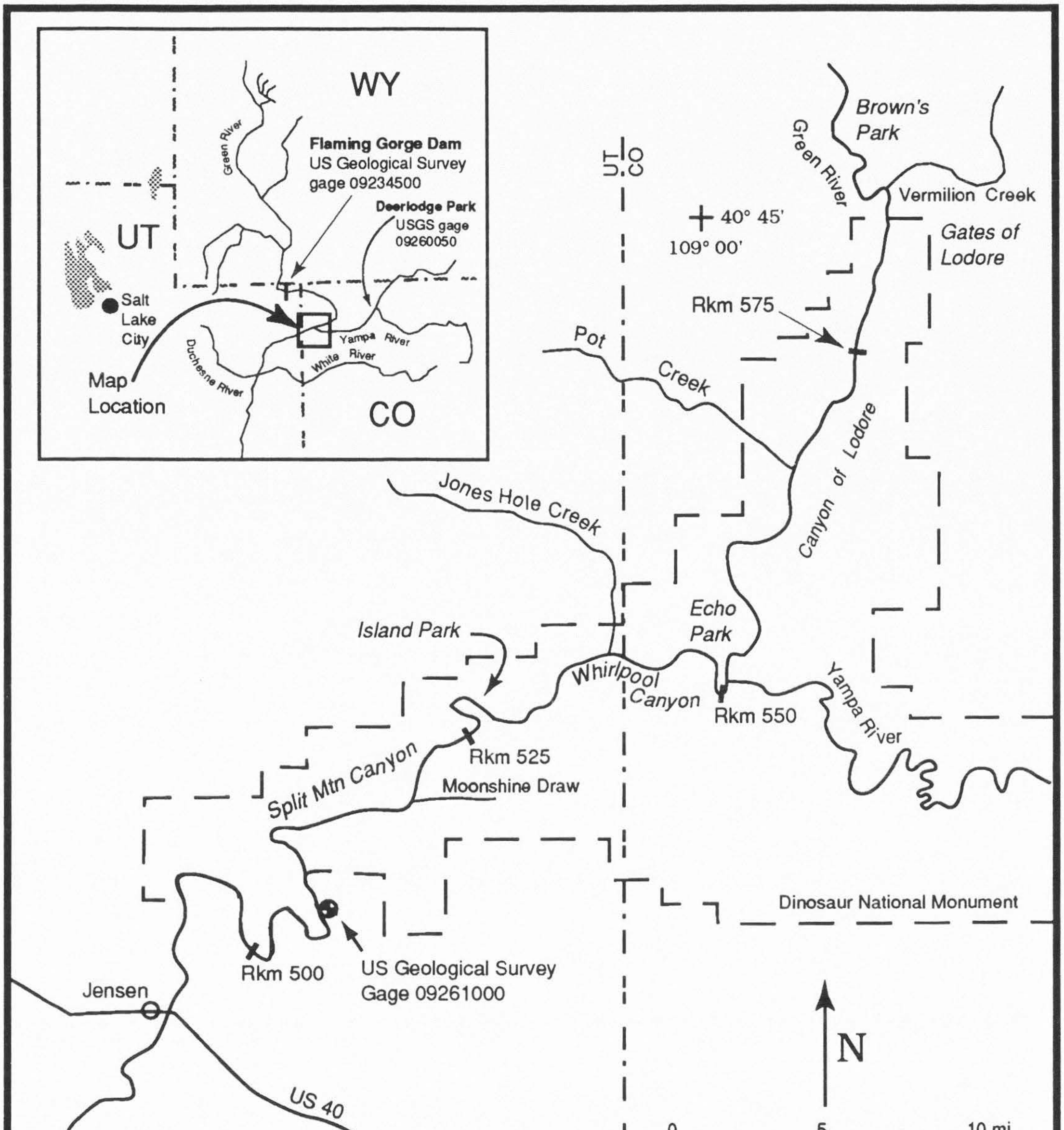


Figure 1. Map showing location of study area. Labeled distances are in km upstream from the Colorado River confluence (Rkm). The location of geomorphic subreaches, major tributaries, and U. S. Geological Survey stream-gaging stations are also indicated.

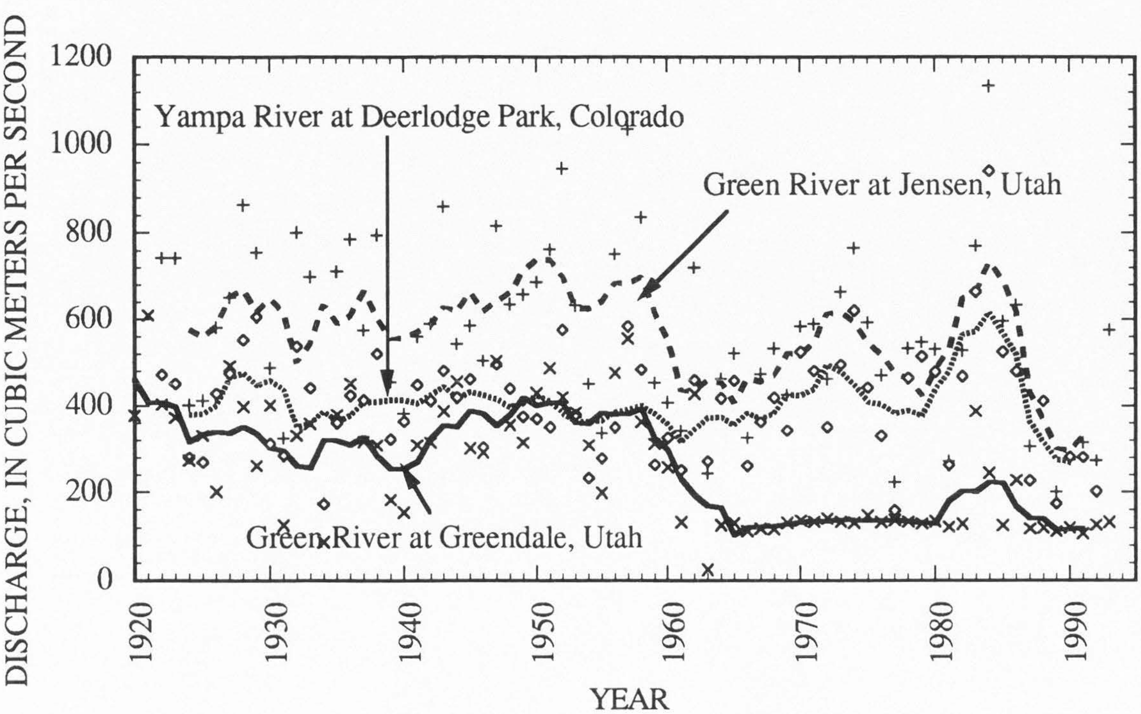


Figure 2. Annual maximum discharge of the Green River near Greendale and Jensen, Utah, and the Yampa River at Deerlodge Park, Colorado. Greendale data are depicted with x's, Jensen data with +'s, and Deerlodge Park data with ◊'s. Fitted lines are 5-yr moving averages. The records for Greendale 1920-1950, Jensen 1922-1946, and Deerlodge Park 1922-1981 are determined by gage-station correlation reconstructed by Schmidt (1994). Flaming Gorge Dam began storing water in 1963.

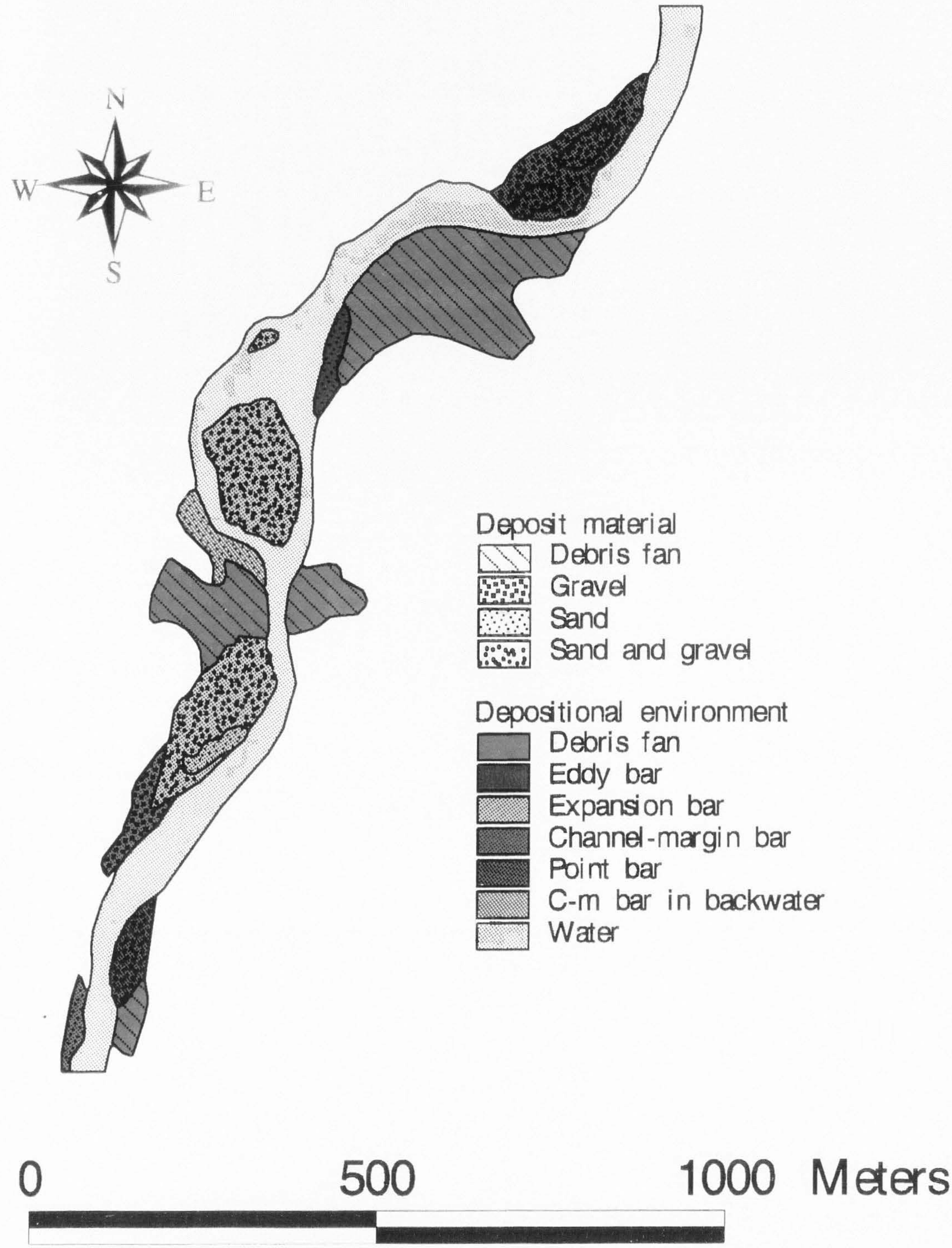


Figure 3. Surficial geologic map of reach in Lodore Canyon showing typical reach with abundant gravel. The upstream debris fan is at Rkm 568.1. Direction of streamflow is from north to south. Fine-grained alluvium is shown by fine dots; coarse-grained alluvium is shown by heavy dots; debris fan material is shown by diagonal lines; unshaded area is bedrock and talus. Depositional environments are labled.

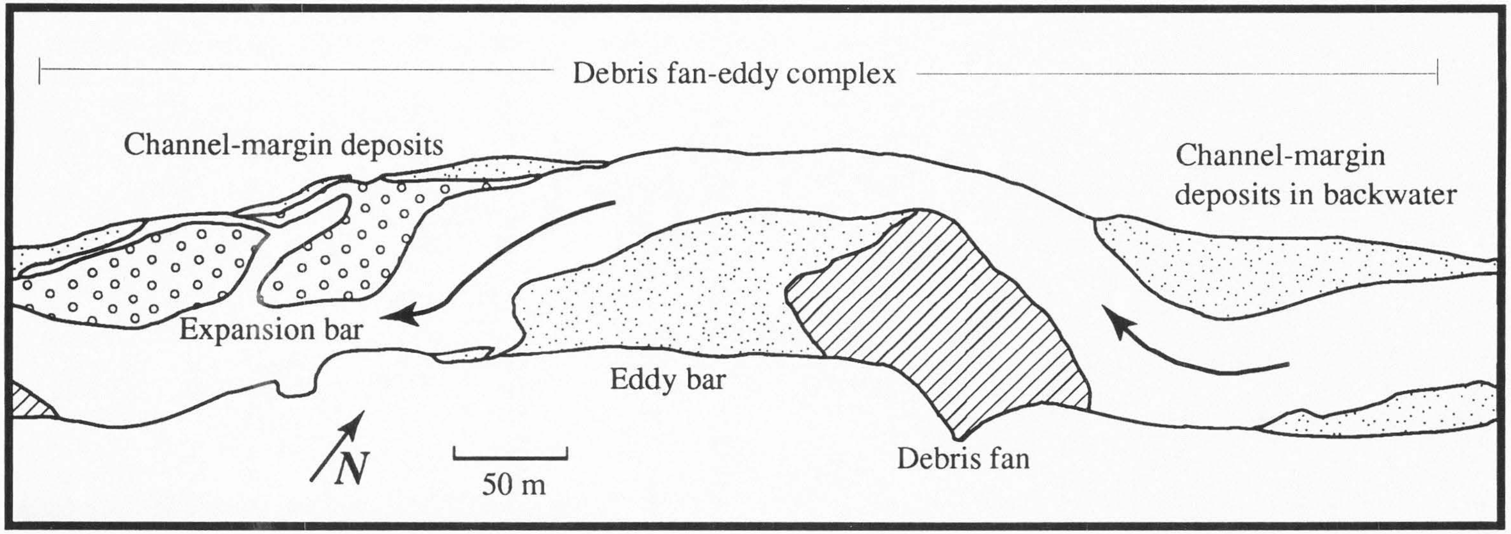


Figure 4. Map of surficial geology at Rkm 563.9 in Lodore Canyon showing typical reach with a fan-eddy complex. Fine-grained alluvium is shown by fine dots; coarse-grained alluvium is shown by heavy dots; debris fan material is shown by diagonal lines; unshaded area is bedrock and talus. Streamflow direction is indicated by arrows and the rapid is shown by wavy lines. During bankfull flow the lower one-half of the eddy bar is inundated by recirculating flow and the gravel expansion bar is mostly inundated by shallow downstream flow.

Figure 5. Photograph of Island Park reach taken during low discharge in October 1995. The view is to the northwest, and streamflow is from right to left. Note the large mid-channel bars and wide terraces, abundant in this reach. This is termed a restricted-meander reach because the channel is intermittently constrained by bedrock on one bank and otherwise free to meander.

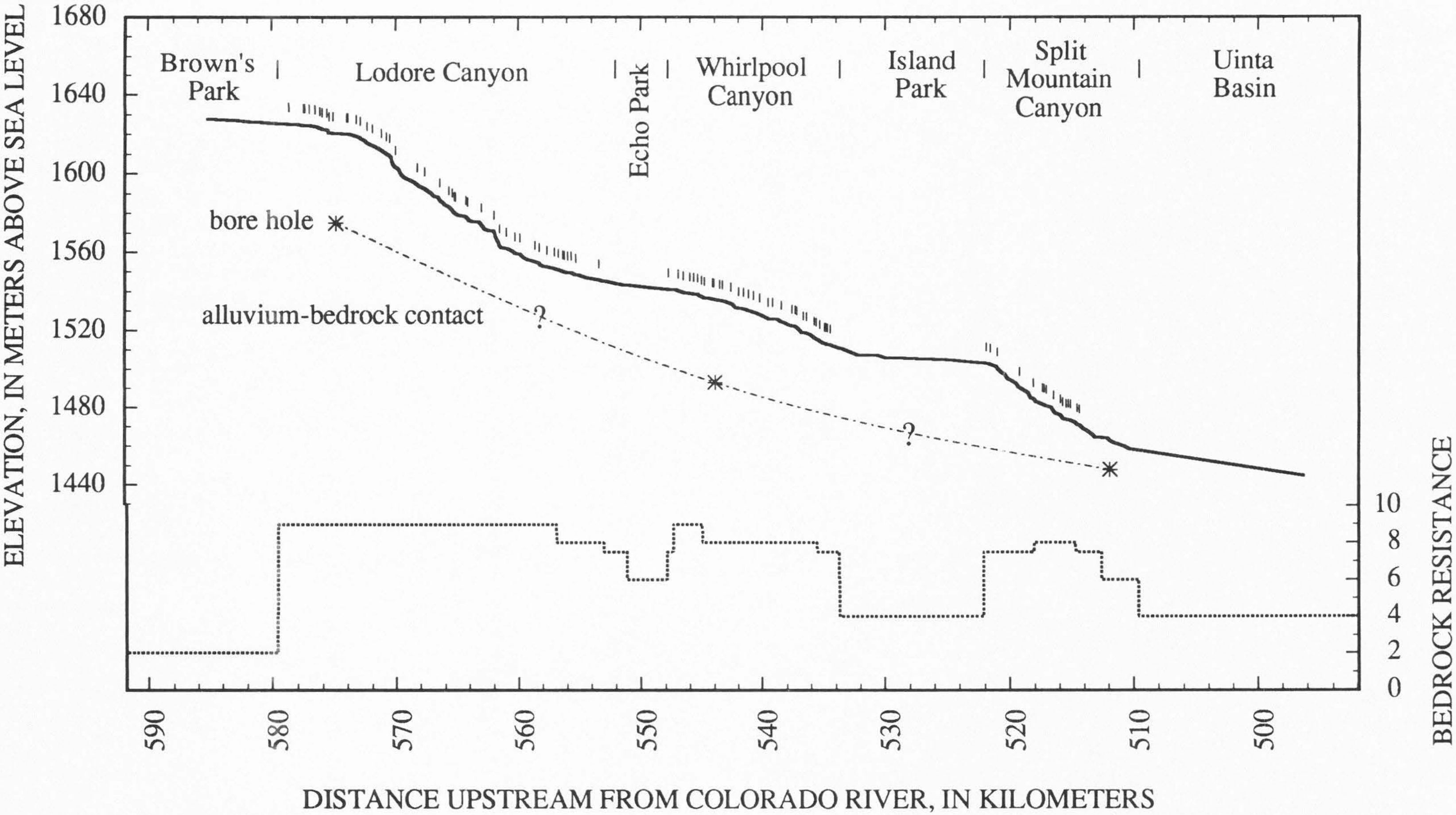


Figure 6. Longitudinal profile of the Green River through the study reach. The solid line is the water surface profile from the U.S. Geological Survey (1924) and the "I" symbols show the locations of tributary debris fans. Depth to bedrock in the river channel is shown at three bore-hole locations. The dashed alluvium-bedrock contact is interpolated from the three data points. Resistance of bedrock that outcrops at river level is shown on the right axis; bedrock resistance scale adapted from Harden (1990).

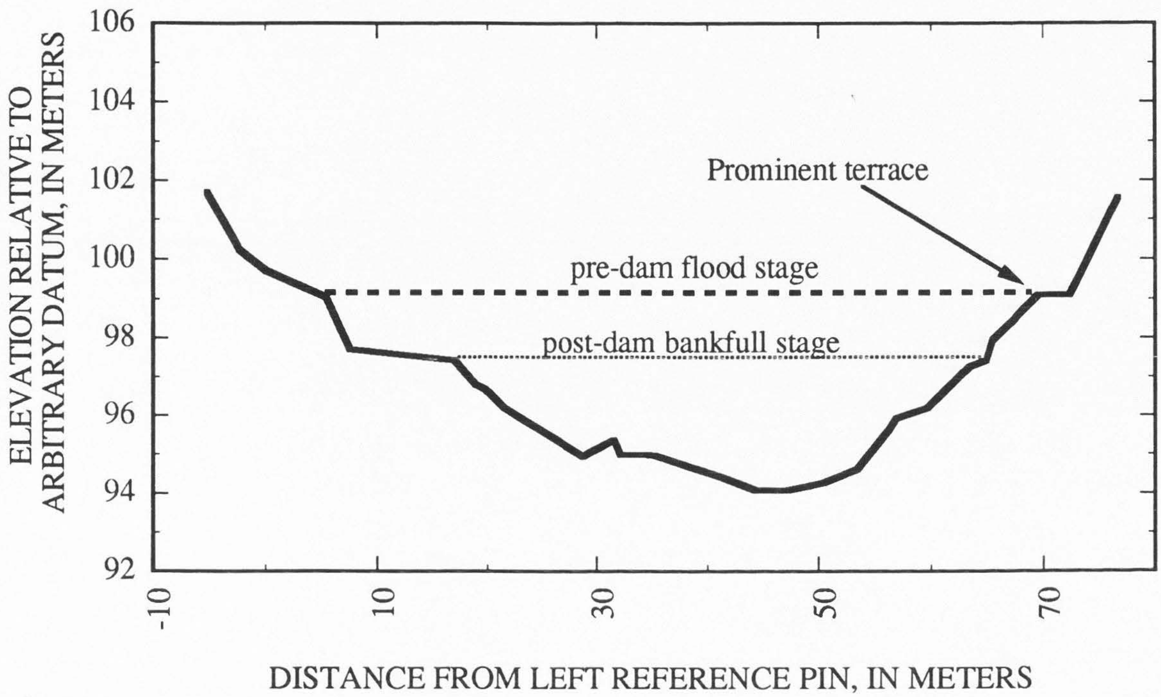


Figure 7. Example channel cross section in Lodore Canyon at Rkm 563.0. The terrace height used to estimate the pre-regulation flood level is indicated by the heavy dashed line. This terrace is composed of fine-grained alluvium and is discontinuous through the study reach.

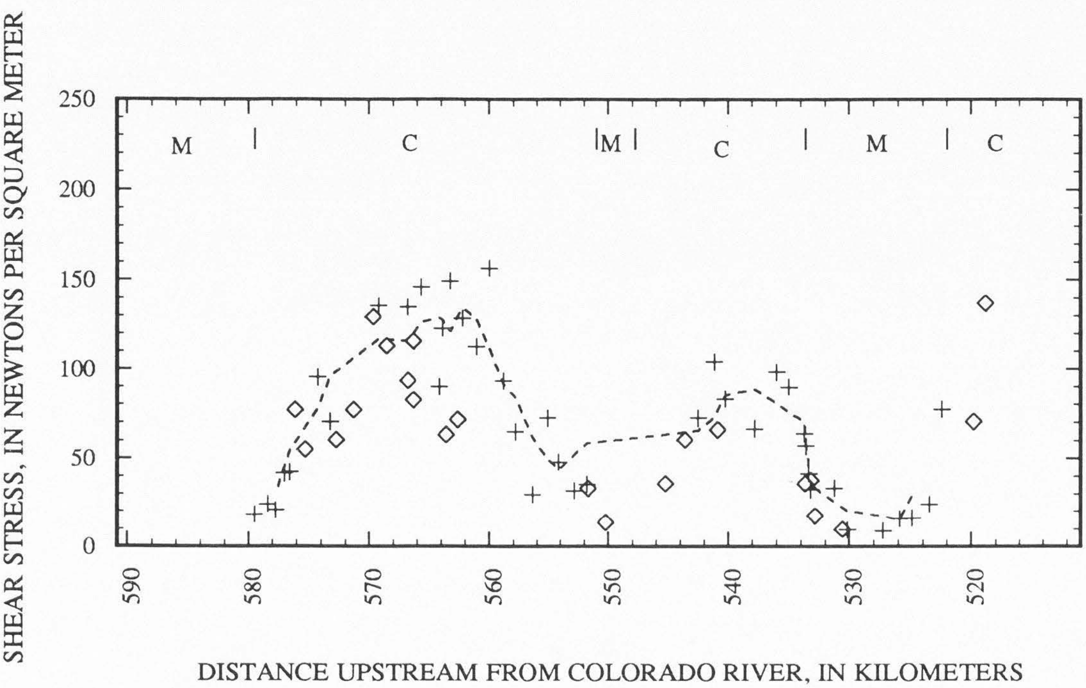


Figure 8. Comparison of average boundary shear stress and critical shear stress. Estimated average boundary shear stress is shown by +'s, and critical shear stress is shown by ◊'s. Canyon and meandering reaches are indicated by C's and M's, respectively. Average boundary shear stress calculated for pre-dam bankfull flow using estimated bankfull surfaces to define channel geometry. Dashed line shows 5-point moving average of average boundary shear stress. Critical shear stress calculated from the Shields function using 0.033 for the dimensionless critical shear stress.

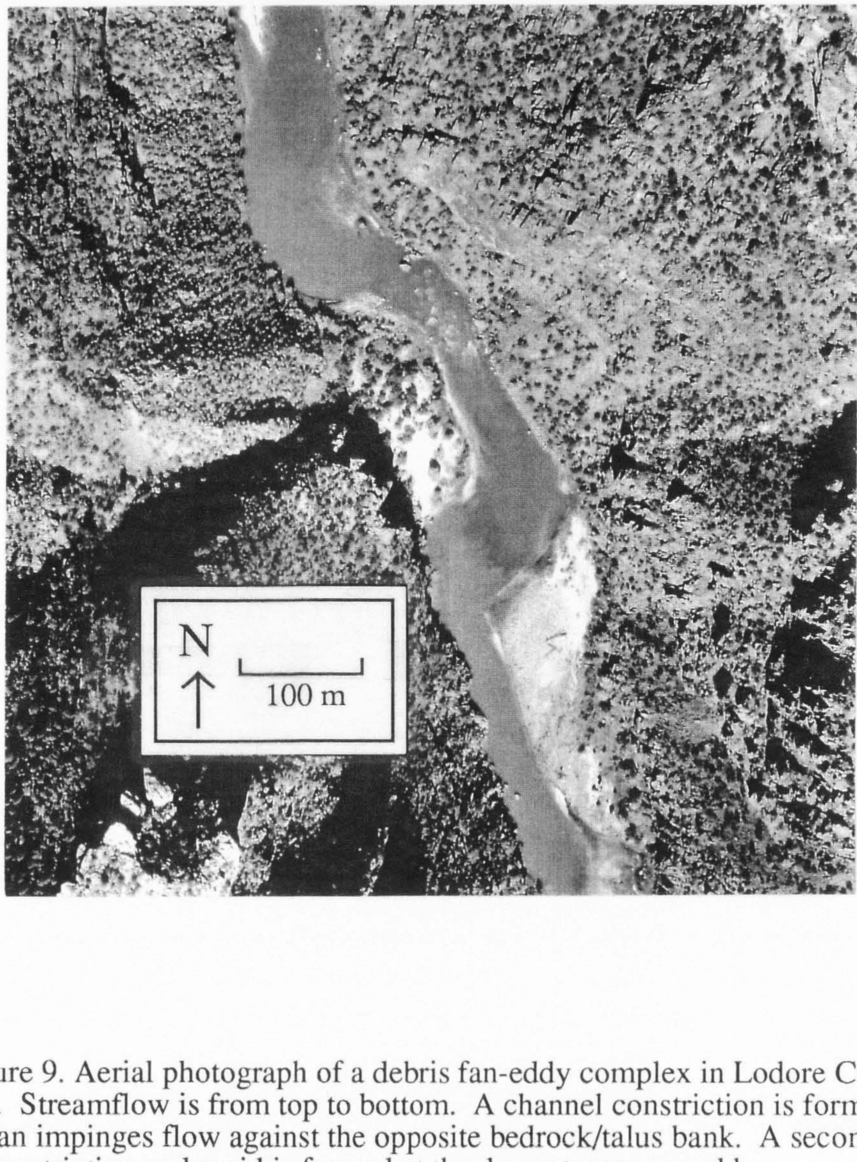


Figure 9. Aerial photograph of a debris fan-eddy complex in Lodore Canyon at Rkm 558.3. Streamflow is from top to bottom. A channel constriction is formed where the debris fan impinges flow against the opposite bedrock/talus bank. A second low-discharge constriction and rapid is formed at the downstream gravel bar.

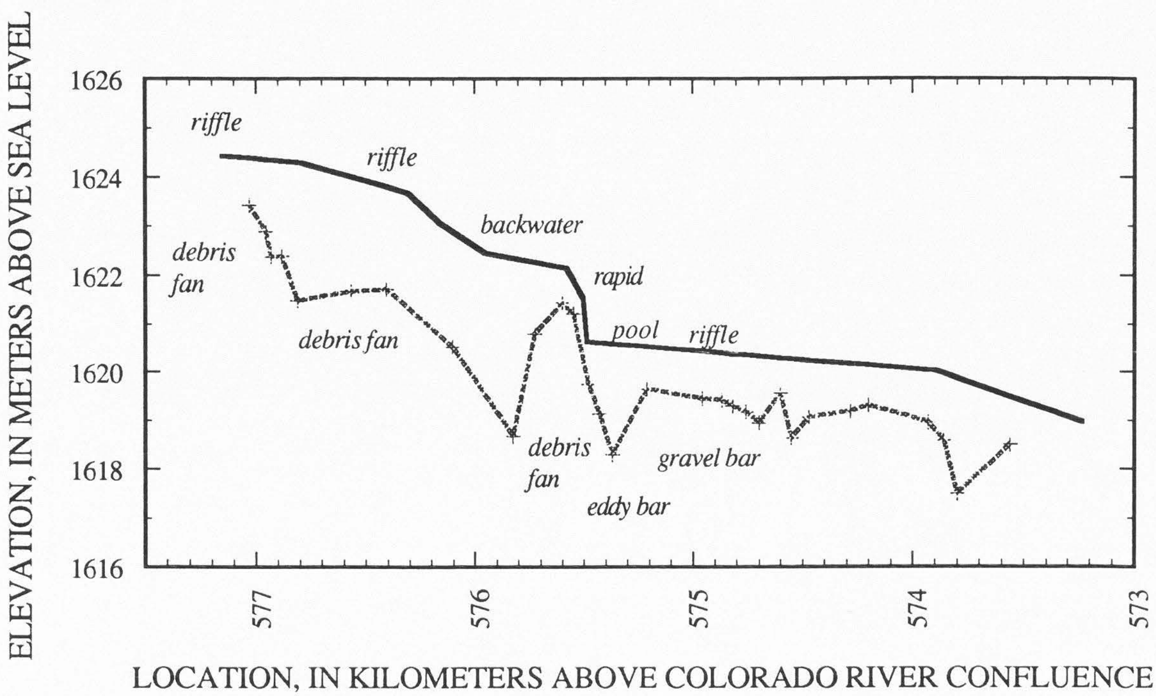


Figure 10. Water surface and bed profile through a fan-eddy complex at Rkm 575.99 (Winnie's Grotto) in Lodore Canyon. The solid line shows water surface and the dashed line shows the riverbed. The +'s show measurement locations. Where debris fans are frequent some fans lack a backwater above and a downstream gravel bar.

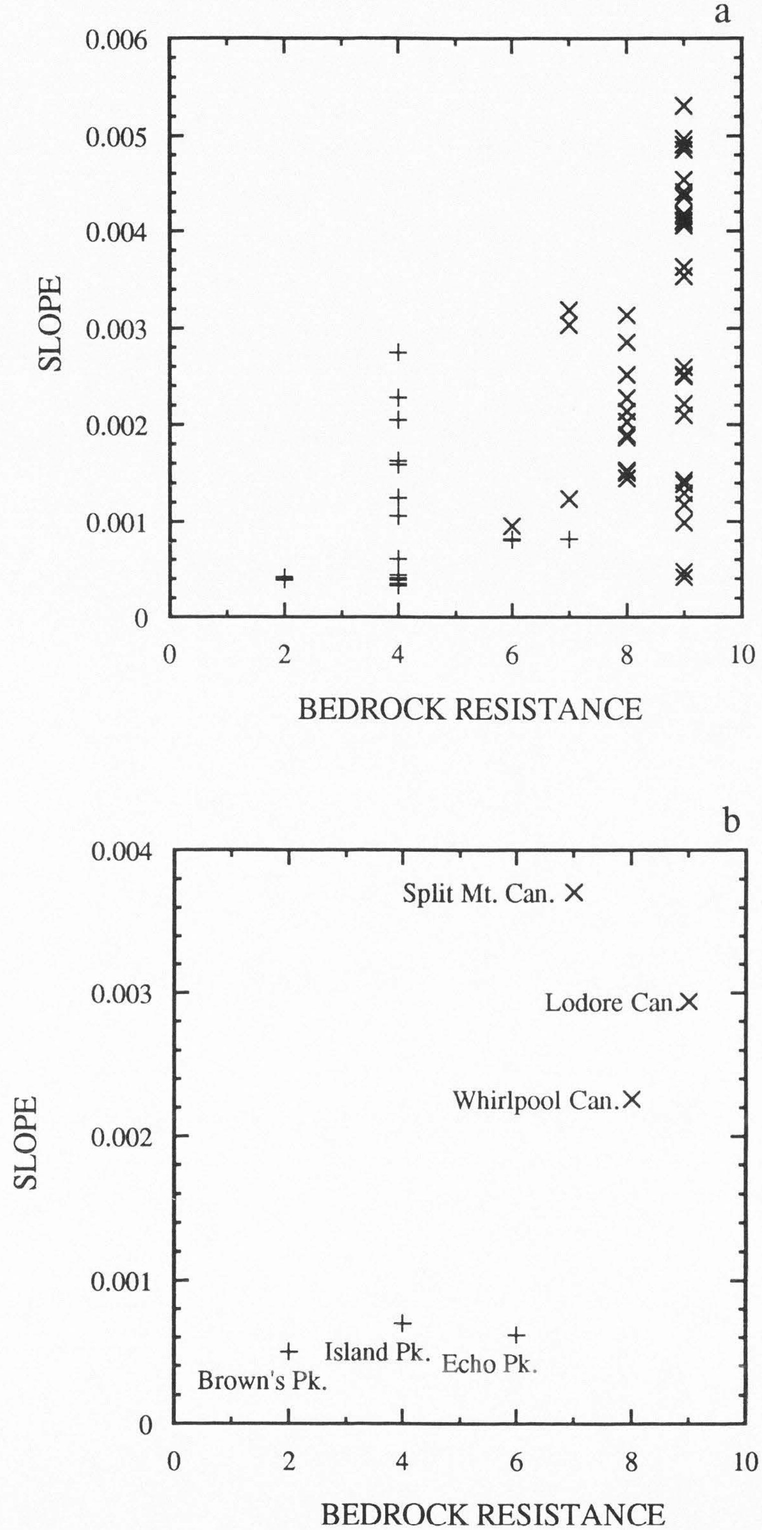


Figure 11. The relationship between resistance of bedrock exposed at river level and water-surface slope of the Green River. Each parameter is measured at 1-km intervals (a); and averaged for each geomorphic subreach (b). Meandering reaches are indicated by +'s and canyon reaches are indicated by x's.

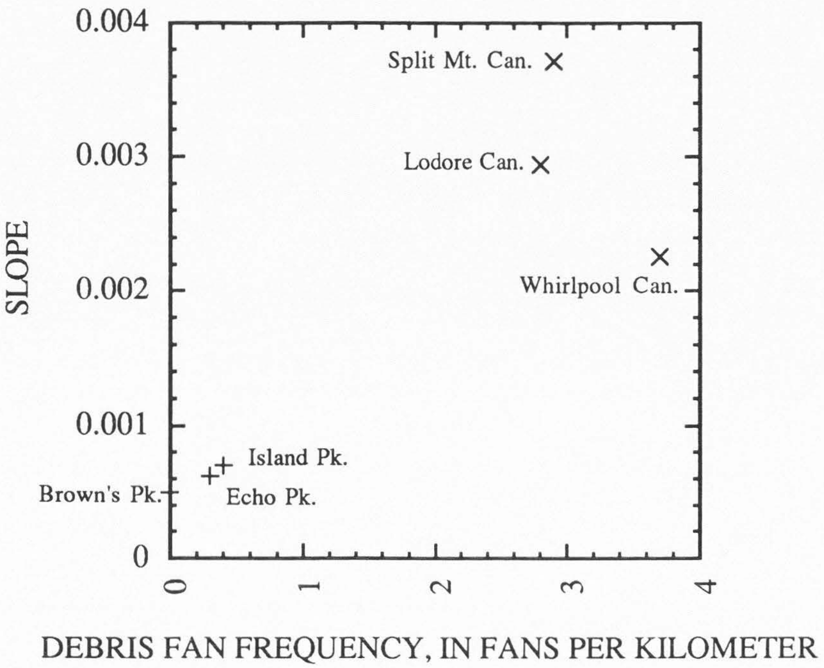


Figure 12. Relation between debris fan frequency and slope of the Green River. Fan frequency was determined from 1:5,000 scale aerial photographs. Meandering reaches are indicated by +'s and canyon reaches are shown by x's.

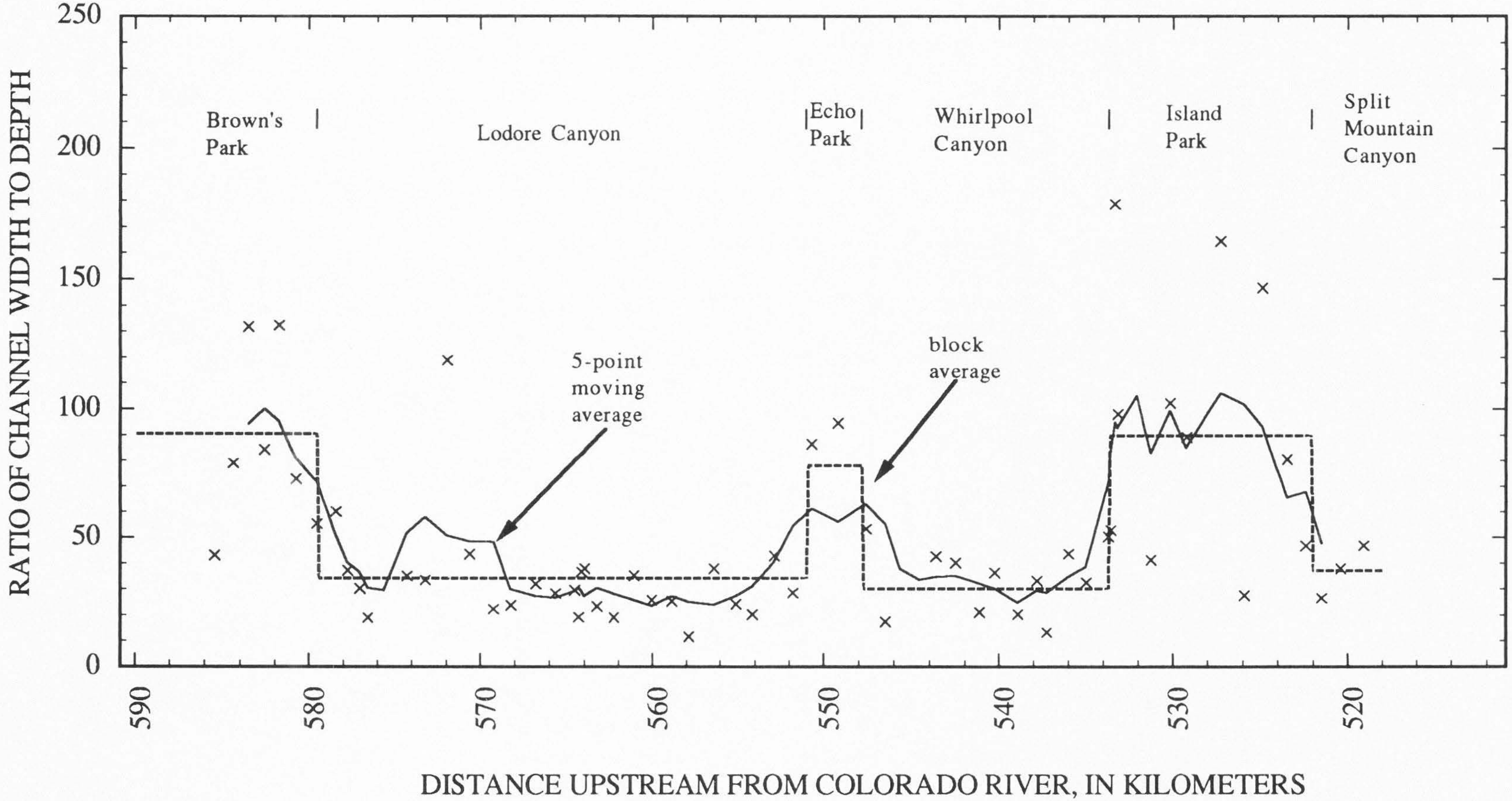


Figure 13. Downstream variation in channel width-depth ratio calculated at post-Flaming Gorge Dam mean annual flood. Solid line shows 5-km moving average and dashed line is block averages for indicated geomorphic subreaches. Channel geometry is similar within each subreach and distinct between subreaches.

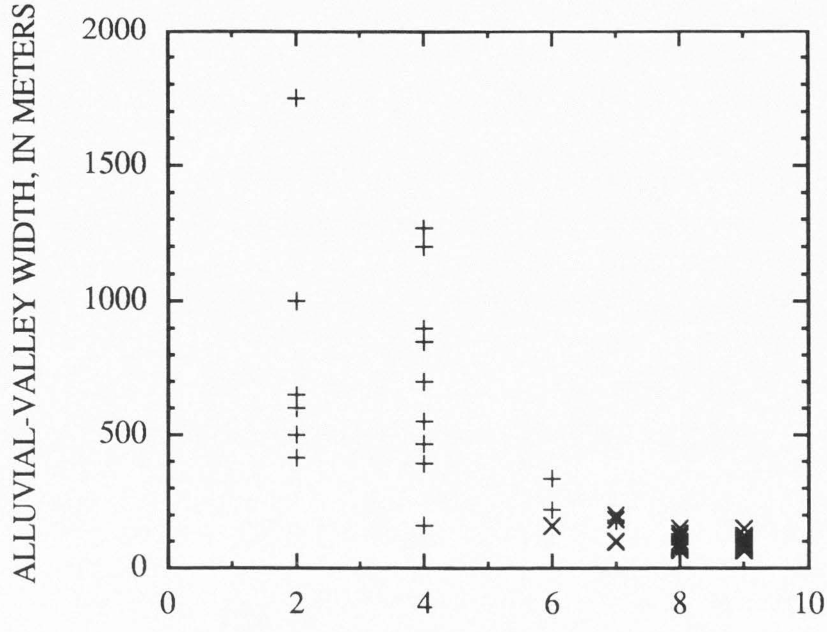


Figure 14. Scatter plot showing the inverse relation between alluvial valley width and bedrock resistance. Each parameter is measured at 1-km intervals. Measurments made in meandering reaches are indicated by +'s and measurements in the canyon reaches are indicated by x's.

CHAPTER 3

CHANNEL NARROWING ALONG THE GREEN RIVER IN THE CANYONS OF THE EASTERN UINTA MOUNTAINS, COLORADO AND UTAH

Introduction

The relationship between fluvial landforms, the river channel, and hydrology is of long-standing interest to geomorphologists, and concepts such as bankfull discharge, effective discharge, and the active flood plain are dominant paradigms (Wolman and Miller, 1960; Andrews, 1980). However, continuing geomorphic research about an ever-widening array of channel types (Nanson, 1986; Pizzuto, 1994) suggests that these paradigms must be reassessed within this broader context.

River channels in narrow canyons are one of those channel types where fluvial landform and channel relationships can be expected to deviate from the original active flood plain-effective discharge paradigm. Stage-to-discharge relations are steep, shear stresses at flood stage are very high, bed material is very coarse, and macroturbulance is significant (Baker, 1984). The abundance of coarse material suggests that landforms along canyon rivers should be insensitive to the kind of hydrologic changes that lead to disequilibrium along wider alluvial rivers. Thus, fluvial landform adjustability, essential to maintaining consistent flood plain-channel relationships, may not exist in canyon rivers.

The purpose of this chapter is to describe the history of channel adjustment that has occurred during the past century along the Green River in the canyons of the eastern Uinta Mountains. The results presented show that the bed and banks of the channel are made up of coarse- and fine-grained sediments, that both these elements are adjustable, that longitudinally correlative flood plain-like features exist, and that they occur at multiple elevations as a result of changes in hydrology and sediment transport that have occurred during the past 50 yr. The results presented here are not only of interest to geomorphologists, but also to river managers who seek improved understanding of the relationship between dam operations and the condition of the downstream channel.

Previous Research

Fluvial landforms such as flood plains, sand bars, and gravel bars are temporary storage sites of sediment, affect local channel geometry and hydrology, and provide habitat for many plants and animals. Investigations into processes of flood-plain formation and the relationship between fluvial landforms, river hydrology, and sediment transport have traditionally concentrated on unconstrained meandering rivers (Wolman and Leopold, 1957; Everitt, 1968; Andrews, 1980). In free-meandering streams, flood plains are created by channel meandering through point-bar formation and lateral accretion (Mackin, 1937; Wolman and Leopold, 1957). The constructed surface is usually associated with bankfull discharge and is inundated on the order of once every 1 to 2 yr (Andrews, 1980). The effort to relate channel form to hydrology and sediment transport resulted in the development of the concept of effective discharge which is the discharge that, over a period of years, transports a majority of the rivers' sediment load (Wolman and Miller, 1960). Recent research has shown effective discharge and bankfull discharge to be the same for self-formed alluvial channels in the Yampa River basin, Colorado (Andrews, 1980). This is a strong argument for the existence of an equilibrium channel form that is adjusted to the streamflow regime.

However, many rivers do not freely meander and concepts developed on these rivers may not apply to other channel types. Ikeda (1989) described conditions where the degree of channel confinement affects channel planform and flood-plain formation. He identified four types of meander patterns in which the degree of channel confinement is progressively greater. The four types are (1) free meanders, (2) confined-free meanders, (3) restricted meanders, and (4) fixed meanders. In confined systems, channels meander less, vertical accretion is a more important flood-plain forming process, and disequilibrium between channel and flood-plain elevation is common (Nanson, 1986). Schmidt and Rubin (1995) proposed that debris fan-dominated canyons are a special case of fixed meanders. In addition to being located within narrow canyons where channel migration cannot occur, depositional processes and channel characteristics are strongly influenced by the presence of numerous channel controls created by debris fans located at tributary entrances. It was demonstrated in Chapter 2 that the Green River in the eastern Uinta Mountains of Colorado and Utah contains both debris fan-dominated canyons and reaches of fixed and restricted meanders.

Vertical accretion has long been recognized as a process of flood-plain formation that is secondary to lateral accretion on free-meandering rivers (Wolman and Leopold, 1957), but recent research shows that vertical accretion may be more important in some systems. Everitt (1968) calculated 2.0 to 3.2 m of vertical flood-plain aggradation based on cottonwood tree germination elevations and dates on the Little Missouri River in North Dakota. Everitt (1968) concluded that overbank deposition is an important process that elevates flood plains along meandering rivers and that, under stable climatic conditions, the rate of deposition decreases exponentially with time due to the progressive increase in elevation of the flood plain. In canyon-bound rivers, lateral channel migration is limited, the stage-to-discharge relation is steep, and vertical accretion occurs when suspended load is evenly distributed in the water column and flows are over bank. Nanson (1986) presented a model of vertical flood-plain aggradation and catastrophic stripping for fixed-meander streams without debris fans in which suspended material accumulates vertically, forming flood plains that gradually become elevated above the riverbed. As the flood plain aggrades, the stage of the bankfull discharge, the discharge necessary to just reach the level of the flood plain, increases. The elevations of these flood plains are not longitudinally correlative, and separate flood plains occur at different stages of accretion. Thus, individual flood plains respond differently to a given flood event, and rapid flood-plain erosion occurs in response to a wide range of flood magnitudes, between the 3.8- and 52-yr event. Thus, the suite of flood plains formed at different elevations represent floods of different magnitudes.

In contrast, Schmidt and Rubin (1995) described longitudinally correlative flood-plain deposits in debris fan-dominated canyons. This is an apparent paradox because one would expect to find better longitudinal correlation of flood plains along a fixed-meander river without abundant debris fans than in a debris fan-dominated canyon with many local channel controls. The deposits identified by Schmidt and Rubin (1995) in Grand Canyon exist at three discrete levels, one that occurs at a stage approximately equal to the stage of the effective discharge and two that formed during discrete large floods. The debris fan-dominated canyons of the Green River provide a setting in which to examine the applicability of the concepts of Nanson (1986) and Schmidt and Rubin (1995) in a system that has both fixed meanders and debris fans.

Disequilibrium flood-plain development has been described in less constrained meandering channels as well. Pizzuto (1994) described a model of flood-plain evolution on the Powder River in Montana where there is neither an equilibrium channel form nor a unique channel-forming discharge. Pizzuto (1994) identified two distinct geomorphic surfaces: a valley flat and a low-elevation bench which aggrade in response to large annual floods and moderate annual floods, respectively. Channel morphology, in this case, reflects multiple formative discharges and is not well represented by a model that proposes a single channel-forming discharge (Pizzuto, 1994). The formation of multiple surfaces in response to different magnitude events in a single hydrologic regime has not been demonstrated elsewhere and may be unique to vertically aggrading systems.

The suite of fluvial landforms found in the confined reaches of the Colorado River in Grand Canyon has been described by Schmidt and Rubin (1995), who defined fan-eddy complexes as the fundamental geomorphic unit in canyons with abundant debris fans. These complexes include the fine-grained channel-margin deposits and eddy bars that form within the backwater upstream from the debris fan, the constricting debris fan that is a channel control at some discharges, the channel expansion and associated eddy bars immediately downstream from the fan, and expansion gravel bars located downstream from the eddy. The expansion bars form where there is an expansion in the width of the zone of downstream-directed current downstream from the narrow constriction formed by the debris fan and eddy (Chapter 2). Schmidt and Leschin (1995) identified more than 150 of these fan-eddy complexes along 29 km of the Colorado River in Grand Canyon.

The annual change in elevation of the alluvial bed and banks of rivers in debris fan-dominated canyons has been a recent research focus (Graf and others, 1991; Wiele and others, 1996). Repeat measurements of monumented channel cross sections are one method that may be used to document changes in bed and bank morphology and sediment storage (Pizzuto, 1994; Graf and others, 1995). Graf and others (1995) found that tributary floods that contribute large amounts of sediment to the Colorado River below Glen Canyon Dam cause bed aggradation. Pizzuto (1994) reported bed and bank scour and valley-flat aggradation on the Powder River in response to the largest flood on record. During the 13 yr following this large flood, repeat surveys documented gradual decrease in channel area as inset benches were deposited adjacent to the channel. It was shown in Chapter 2 that the channel of the Green River in the eastern

Uinta Mountains consists of a self-formed alluvial channel inset within a bedrock-confined canyon. This study utilizes repeat measurements of channel cross sections to evaluate the annual adjustability of the channel where annual peak flows are 50 percent and 75 percent of preregulation magnitude.

Most studies on the downstream effects of dams have been conducted on alluvial rivers and have focused on degradational effects near the dam which decrease downstream (Williams and Wolman, 1984). The effects of large dams on downstream alluvial deposits have also been evaluated in some debris fan-dominated canyons. Schmidt (1990) and Schmidt and Graf (1990) concluded that fluctuating flows released from Glen Canyon Dam cause erosion of some eddy-deposited sand bars but the effect of the dam does not systematically decrease downstream. Post-dam floods that occurred between 1983 and 1986 eroded eddy bars in the most narrow reaches of Grand Canyon but aggraded those in wider reaches documenting a sensitivity to local channel controls (Schmidt, 1990; Schmidt and Graf, 1990). Grams (1991) measured an exponential decrease with time in the number and surface area of eddy-deposited sand bars downstream from Hells Canyon Dam on the Snake River in Hells Canyon, Idaho. Grams (1991) argued that most of the erosion occurred during the first large floods following dam closure, a result consistent with studies on alluvial streams (Williams and Wolman, 1984). Subsequent large floods have had less impact due to channel adjustment and lack of sediment resupply. Schmidt and others (1995) compared the Grand Canyon and Hells Canyon systems and concluded that the higher rate of erosion measured in Hells Canyon is due to larger post-dam floods and no tributary sediment supply in Hells Canyon. The downstream effects of a dam, therefore, vary dependent upon (1) the degree of hydrologic alteration, (2) the availability of downstream sediment supply, and (3) local channel characteristics. Examination of channel changes along a variety of regulated rivers is needed to improve our understanding of the relative importance of these factors and to better predict the effects of dam operations on the downstream channel.

The downstream effects of Flaming Gorge Dam on the sediment load of the Green River were evaluated by Andrews (1986). Although the volume of the mean annual runoff has not been affected by flow regulation, the reduction of peak flows has reduced the annual sediment load by 54 percent near Jensen, Utah, 169 km below the dam and 48 percent at Green River, Utah, 467 km downstream (Andrews 1986). Pre- and post-impoundment sediment budgets calculated by Andrews (1986), which assume that the preregulation Green River was in long-term quasi-equilibrium and that tributary sediment input has not changed, predict that channel erosion is occurring in the 105-km long reach that extends from the dam to the Yampa River confluence. Further downstream, tributary resupply of sediment has led to equilibrium or aggradational reaches (Andrews, 1986). Measurements of pre- and post-dam bankfull channel width from aerial photographs, however, show that narrowing has occurred in all three reaches (Andrews, 1986). Narrowing in the reach upstream from the Yampa River was attributed to degradation and entrenchment while channel narrowing below the Yampa River was attributed to bank accretion. Lyons and others (1992) measured channel widths on historical photographs and found no significant changes between 1952 and 1964, supporting Andrews' (1986) assumption that the preregulation river was in quasi-equilibrium. Lyons and others (1992) clarified the time intervals of channel change and measured channel narrowing between 1964 and 1974, which was followed by a 4-yr period of no change. Between 1978 and 1986 there were annual floods of preregulation magnitude and Lyons and others (1992) measured an increase in channel width. No measurements were made to document changes after 1986. Lyons and others (1992) observed that channel narrowing occurs primarily by the attachment of islands to banks by aggradation in side channels. All measurements of channel width were made in restricted-meandering alluvial reaches, and no studies have quantified changes in channel morphology in canyon reaches of the Green River. Recent investigations downstream from the Uinta Mountains (Mayers and Schmidt, 1994) confirmed that post-dam channel narrowing has occurred in meandering reaches downstream from the Yampa River confluence. The present study describes channel change in unstudied reaches of the Green River where Andrews (1986) predicted channel erosion upstream from the Yampa River confluence or equilibrium conditions further downstream.

Description of Study Area

The Green River in the eastern Uinta Mountains has been divided into five geomorphically distinct subreaches based on channel geometry and gradient (Chapter 2). Three of the reaches are debris fan-dominated canyons: Lodore Canyon, Whirlpool Canyon, and Split Mountain Canyon. These reaches have low channel width-to-depth ratios, steep gradients, and abundant debris fans and rapids (Chapter 2). Echo Park and Island Park are meandering reaches and have higher width-to-depth ratios, much lower gradients, and very few debris fans. For example, the average ratio of channel width-to-depth is 33.3 in canyon reaches and 74.7 in meandering reaches, and gradient averages 0.0021 in canyon reaches and 0.0008 in meandering reaches (Chapter 2).

The study reach consists of two hydrologically distinct reaches. Flow of the Green River is completely regulated by Flaming Gorge in the 105 km reach between the dam and the Yampa River confluence at Echo Park (see Fig. 1). The U. S. Geological Survey gaging station near Greendale, Utah (station number 09234500), immediately downstream from the dam, measures flow for this reach. The typical pre-dam hydrograph was dominated by spring snowmelt-runoff and low fall and winter baseflows. The pre-dam mean annual flood was 334 m^3s^{-1} and has been reduced by about 63 percent to 139 m^3s^{-1} since dam closure (see Fig. 2). The volume of total annual runoff and the mean annual discharge have not been affected by the operations of Flaming Gorge Dam. The shape of the annual hydrographs has, however, changed substantially (Fig. 15). The pre-dam hydrograph peaked in spring and low base flows occurred during the winter. Flows between the range of the peak powerplant operating capacity (between 100 and 127 m^3s^{-1}) now occur between 9 and 16 percent of the time compared to 4 percent of the time in the pre-dam period. Base flows are now higher than in the pre-dam period.

The unregulated flows from the Yampa River, which has the same mean annual runoff as the Green River above the confluence, join the Green River at Echo Park. The mean annual flood of the Yampa River measured and estimated at Deerlodge Park, Colorado (station number 09260050), is unchanged for the period of record and is similar to that of the Green River prior to construction of Flaming Gorge Dam (Fig. 16). The combination of regulated and unregulated flow from the Green River and the Yampa River, respectively, decreases the effects of Flaming Gorge Dam to a 26 percent reduction in the mean annual flood at the gaging station near Jensen, Utah (station number 09261000), 46 km downstream from Echo Park. The recurrence intervals for floods of greater magnitudes have been similarly reduced (Fig. 16).

Post-dam floods have occurred on the Green River in 1983, 1984, and 1986 in response to unusually wet conditions that filled Flaming Gorge Reservoir (Fig. 16). The highest flow in Lodore Canyon was 388 m^3s^{-1} at Greendale, Utah, and occurred in 1983. The 1984 flood was highest flow downstream from Echo Park, the result of high flows from the Yampa River, and peaked at 1,133 m^3s^{-1} near Jensen, Utah. The 1983 peak in Lodore Canyon was equivalent to the flood with a pre-dam recurrence interval of about 3 yr (Fig. 16). The 1984 peak downstream from the Yampa River confluence was the highest flood on record, pre- and post-dam. Excluding the 3 yr of rare floods, the average post-dam peak dam release at Greendale, Utah is 126 m^3s^{-1} and the highest release was 146 m^3s^{-1}, which occurred in 1975.

Closure of Flaming Gorge Dam has significantly affected sediment transport above and below the Yampa River confluence as well. Sediment sources between Flaming Gorge Dam and Echo Park are limited to the bed and banks of the river and ungaged tributaries. The largest tributaries, Red Creek and Vermillion Creek, enter the Green River 18 km and 70 km downstream from the dam, respectively (Fig. 15). The only site with a long-term record of sediment transport near the study area is the gage near Jensen, Utah. Since 1963, the mean annual load of suspended sediment has been reduced by about 54 percent at this site, from 6.28 x 10^6 Mg to 2.91 x 10^6 Mg (Andrews, 1986).

Methods

Channel Cross Sections

We measured 67 channel cross sections spaced at approximately 1-km intervals from Brown's Park to Split Mountain Canyon to characterize channel geometry, identify bed material, and establish long-term channel monitoring sites. These cross sections were established in 1994 during low discharge using a geodetic total station and depth-recording echo sounder. Cross-section endpoints were monumented with fence posts or rebar that also serve as local elevation control points. Measurements were made by fixing a steel or kevlar tag line between the endpoints and measuring depth at 3.1-m intervals. The echo-sounding transducer was mounted on a pole attached to a raft; boat position was held under the tagline by the boat operator using oars or an outboard motor. The echo sounder was operated by a second person on the boat who labeled tag-line marks on the paper trace. Other researchers using similar methodology have used up to 10 passes (Graf and others, 1995) to reduce directional bias and boat-positioning error. We found that by moving the boat slowly and steadily, we were able to mark points accurately and obtain repeatable measurements with four to six passes. Accuracy was evaluated by repeating measurements with the total station for those points where water depth was less than 1.5 m. Echo-sounder determined depths and surveyed depths are correlated with an R^2 of 0.99. The standard deviation of the four to six passes was calculated and was typically less than the thickness of the line used to plot the bed profile. Large errors in measured depth occurred only near the banks where depth changes rapidly. Water-surface elevations were surveyed at the time of each cross-section measurement and include low flows and peak flows. Characteristics such as bed and bank material, high-water marks, and locations of distinct geomorphic surfaces were noted and surveyed at each site. The precise location of each cross section was recorded on aerial photographs (1:5,000 scale) and topographic maps.

The coordinate survey data were reduced into distances and elevations relative to the reference pins. The discharge at the time of measurement was determined from records for the appropriate gage station. Water stage travel time is less than 1 day between the study area and the respective gage station, daily flow fluctuations are small, and tributary inputs are minimal. Therefore, the mean daily discharge at the appropriate gage station was taken as the discharge at the time of measurement. The elevation of the water surface at each cross section was interpolated from the longitudinal profile surveyed by the U. S. Geological Survey in 1922 (U. S. Geological Survey, 1924). This profile was surveyed at 1.5-m contour interval over a 2-week period during which the discharge changed an average of 4.4 m^3s^{-1} per day and decreased a total of 25 m^3s^{-1}. This remains the most detailed longitudinal profile available for the Green River that includes more than a 1 to 2 km detailed study reach.

The primary criteria for cross-section establishment were the existence of uniform downstream flow and feasibility of measurement. Thus, cross sections were generally not surveyed in rapids or in large recirculating eddies. Because these areas were avoided, few cross sections traversed eddy bars or gravel bars in flow expansions. Therefore, analysis of channel adjustability from repeat cross-section measurements applies to uniform flow reaches and not to rapids. Observations of bed material in rapids indicates that bed material is coarser and therefore less adjustable in these locations.

We resurveyed about 50 percent of the cross sections in June and August 1995. Most of these sites were resurveyed again in May, June, and September 1996. These measurements were made with the methodology described above. Appendix A contains a list of all the cross sections, their locations, and date and discharge at the time of each survey.

Mapping of Surficial Geology

This study utilizes surficial geologic maps that have been digitized into a geographic information system (GIS) and attributed in a multilayer deposit classification scheme (Chapter 2). Surficial geology was interpreted on aerial photographs (1:5,000 scale) taken in 1993 at low discharge. Discharge at the time of the photographs was about 33 m^3s^{-1} and 45 m^3s^{-1} upstream and downstream from Echo Park, respectively. Photo-interpreted maps were field checked, and the data were transferred to a 1:12,000 scale topographic base map using a reflecting projection table. Completed maps were digitized and a multilayered deposit classification was added to incorporate a maximum amount of information about each deposit into a geographic information system. Three geomorphic attributes were specified for each feature mapped: (1) substrate composition, (2) depositional environment, and (3) geomorphic level of the deposit. Bedrock type at river level adjacent to each deposit and geomorphic subreach in which each deposit was located were determined from geologic (Hansen and others, 1983) and topographic maps. This information was also incorporated in the database. In addition, groups of fine-grained deposits, gravel bars, and associated debris fans were identified as distinct eddy complexes and each was assigned a unique number. Many map units are not part of any eddy complex.

Geomorphic characteristics, area, and perimeter of each mapped deposit in the study reach are tabulated in a GIS database. These data were filtered by geomorphic subreach, depositional environment, and deposit level for analysis. The error in the original maps is ± 2 m, about the width of the line used in the mapping. Because these data were transferred to a base map at a 2.4 times the original scale, the final error is about ± 5 m. The error in areal measurements is estimated to be ± 1 percent of the reported values. This error was determined by comparing the areas of mapped features that have not changed within the past 100 yr, such as Quaternary alluvium and alluvial fans, mapped in the Island Park reach in both 1938 and 1993.

Gravel and sand bars exposed at low water are the only portion of the stream bed that is easily accessible. Bed material size was measured at 18 gravel bars; each bar was sampled at the upstream end below the high-water line. About 100 particles on exposed parts of the bars were sampled at even intervals along a tape measure. Random walk methods were used to sample submerged parts of some bars (Wolman, 1954). Bulk samples of fine-grained alluvium were collected from sand bars, flood plains, and terraces. Size distribution was determined by laboratory sieve analysis using the methods outlined by Guy (1969).

Historical Photography

Historical aerial and oblique photographs are frequently employed as tools to describe changes in geomorphology and vegetation (Webb, 1996). Fifty-seven historical photographs of the Green River through the study area were obtained by archival research at government repositories and university libraries. Copy prints were made of each photograph and taken into the field for replication. Precise replication points were located by parallax between foreground and background features in each photograph. In the absence of distinct foreground features, location was determined by parallax between different background features. Photographs were replicated using a Crown Graphic camera with a 135-mm lens and a 35-mm camera with a 35- to 70-mm zoom lens. Appendix B is a list of each replicated photograph, the original source of the photograph, and the type of match made. Black-and-white prints and color slides were taken of each view. Notes detailing observations were made in the field for each photograph, and measurements of change relative to stable features were made where possible. Each pair of matched photographs was examined for changes in riparian vegetation, evidence of narrowing of the active channel, the number of geomorphic surfaces adjacent to the channel, and change in substrate composition of bars and islands. This information was tabulated by photograph and summarized for each geomorphic subreach.

Historical aerial photographs were used to quantify channel changes. The use of these photos was limited to meandering reaches because the large scale and frequent shadows of early photographs make interpretations in canyon reaches inaccurate. Maps of the Echo Park and Island Park subreaches were made for 1954 and 1938, respectively. These maps were adjusted to a common scale of 1:12,000 using a zoom-transfer scope and a reflecting projector. The final maps were digitized and compared with the 1993 maps in a GIS.

Results

Geomorphology of Alluvial Deposits

Fine-grained deposits occur as four flood plain-like and terrace-like landforms that are longitudinally correlative throughout the study area. These geomorphic surfaces are the active channel deposits, the post-dam flood plain, the intermediate bench, and the cottonwood-box elder terrace. Coarse-grained gravel deposits typically are active channel deposits but occasionally are correlative with the other three levels of fine-grained deposits.

Cottonwood-Box Elder Terrace

The cottonwood-box elder terrace (hereafter, c-b terrace) is the most continuous and extensive feature mapped in the study area and occurs in both canyon and meandering reaches. The name is derived from the cottonwood (*Populus fremontii*) and box elder (*Acer negundo*) trees abundant on this level in meandering and canyon reaches, respectively (Fig. 17). Juniper (*Juniperus osteosperma*), pinyon pine (*Pinus sp.*), sagebrush (*Artemisia sp.*), rabbit brush (*Chrysothamnus sp.*), and ponderosa pine (*Pinus ponderosa*) are also common on this surface. The soil organic layer is up to 15 cm thick and grass is the typical ground cover. The c-b terrace is a fine-grained deposit with a very flat upper surface and occasional river-parallel levees and back channels. Levees are located adjacent to the river channel and back channels are typically on the distal edge of the surface adjacent to bedrock or talus. The c-b terrace level averages 3.3 m above baseflow water surface upstream from the Yampa River confluence and 4.2 m downstream, with standard deviations of 1.0 and 0.9 m, respectively (Fig. 18).

Most exposures showing the stratigraphy of the c-b terrace are dominated by horizontally bedded fine-grained sediment, showing that this terrace formed by vertical accretion. As many as 15 distinct horizontal beds occur in a 2- to 3-m vertical exposure (Fig. 19). Individual beds range in thickness from about 1 cm to more than 50 cm, and the dominant texture of the beds ranges from clay to coarse sand. Many units are massive, but sedimentary structures commonly exist. Typically, beds are composed of medium to very-fine grained tan to brown sand with thin interbeds of coarse red sand in the upper parts of exposures and interbeds of clay lower in the exposures. Buried layers of leaf litter and other organics are also common. Some of the brownish beds are massive, but ripple-drift cross-laminations indicating downstream transport can be found. Upward fining was observed in many bed sequences. The basal unit is typically coarse sand and upper beds are typically rippled medium- to fine-grained sand. The reddish, coarse-sand beds are believed to be slopewash deposits derived from nearby ephemeral tributaries that drain reddish Uinta Group quartzite.

Driftwood on the c-b terrace upstream and downstream from Echo Park includes sawn timbers that indicate inundation by floods that have occurred subsequent to upstream settlement in the late 1800's. U. S. Geological Survey photograph 23416 taken in 1917 (Appendix B) shows the c-b terrace completely inundated just above the beginning of Lodore Canyon. The peak discharge for that year was about 510 m^3s^{-1} which has a pre-dam recurrence interval of about 25 yr. The level of the c-b terrace downstream from the Yampa River confluence was completely inundated during the peak of the 1984 flood at 1100 m^3s^{-1}, the largest flood on record. Thus, only rare historical floods reach the level of the c-b terrace.

Intermediate Bench

The intermediate bench is a flat surface that typically occurs as a strip adjacent to and lower in elevation than the c-b terrace (Fig. 17). Mature tamarisk (*Tamarix sp.*) trees are the most common woody plant on the intermediate bench, but occasional willow (*Salix sp.*) and rare cottonwood trees can be found. Surface organic layers are thin and may consist of only 1 to 2 cm of organic duff. Horsetail fern (*Equisetum sp.*), grasses, and forbes are common ground covers. The intermediate bench averages 1.9 ± 0.7 m and 2.4 ± 0.4 m above baseflow water surface upstream and downstream from the Yampa River confluence, respectively (Fig. 18). Excavations at four sites indicate that the intermediate bench is a depositional unit inset into the c-b terrace. The inset intermediate bench is typically underlain by units of the c-b terrace (Fig. 20). Thickness of the inset varies, but is on the order of 0.5 to 1.5 m. Thus the intermediate bench deposits must (1) postdate the c-b terrace and (2) be formed by depositional events following erosion into the c-b terrace. High-water marks on the intermediate bench in Lodore Canyon indicate that this surface was inundated by the 1983 flood, which peaked at 388 m^3s^{-1}. Downstream from Echo Park the level of the intermediate bench is typically above the stage reached by 485 m^3s^{-1}, which is the highest flow that occurred during the study period. Thus, this surface is likely inundated by flows greater than 600 m^3s^{-1} and is certainly flooded by flows of about 1,000 m^3s^{-1}.

Post-Dam Flood Plain

The post-dam flood plain is the level that is inundated annually in the present streamflow regime. The average elevation is from 0.8 ± 0.3 m above baseflow water surface upstream from the Yampa River confluence and 1.3 ± 0.4 m downstream from the confluence (Fig. 18). A primary diagnostic characteristic of this surface is the presence of young woody riparian vegetation (Fig.19). The most common species are tamarisk, willow, and cottonwood. The post-dam flood plain occurs as channel-margin deposits, eddy bars, and expansion bars. As a channel-margin deposit, it typically forms a narrow bench that is 1 to 5 m wide. On expansion bars, the post-dam flood plain usually consists of a veneer of fine-grained alluvium that forms an apron around the gravel bar, separating c-b terrace level from active gravel.

Because this surface is formed and maintained by the post-dam flow regime, its elevation differs upstream and downstream from the Yampa River confluence. The peak flow in Lodore Canyon is the same every year (Fig. 16) and has a duration of up to 8 weeks (Fig. 15). Thus the deposit associated with these flows forms a very distinct and typically flat surface that is inundated by the post-dam mean annual flood of 143 m^3s^{-1}. The post-dam flood plain downstream from the Yampa River confluence tends to cover larger areas and often occurs as a gentle slope rather than a distinct level bench.

It begins to be inundated in this reach at about 455 m^3s^{-1}, which is the post-dam 2-yr flood.

Active-Channel Deposits

Active-channel deposits consist of alluvium that is typically inundated to a sufficient depth such that bed material is mobilized frequently enough to inhibit the establishment of perennial vegetation. These deposits typically consist of bare sand, bare gravel, or debris with very little or no vegetation. Active deposits also include those that comprise the bed material of frequently inundated, nonvegetated side channels.

Longitudinal Correlation of Geomorphic Surfaces

Each level can be longitudinally correlated throughout the entire study reach, regardless of whether subreaches are debris fan dominated or meandering. The longitudinal profile of these correlated deposits generally reflects the profile of the water surface (Fig. 21). The average distance between baseflow and each deposit surface is less in meandering reaches than in debris fan-dominated reaches; and less upstream from Echo Park than downstream from Echo Park. The downstream variation in elevation for each level is less than the difference in elevation between levels. The statistical significance of the difference in elevation between the three surfaces was evaluated with 2-sample t-tests. The mean elevation of the post-dam flood plain is not greater than or equal to the mean elevation of the intermediate bench; and the mean elevation of the intermediate bench is not greater than or equal to the mean elevation of the c-b terrace, for $\alpha = 0.05$.

Individual fine-grained terraces or flood plains may extend longitudinally for as much as 1 km. The width of these deposits may be several hundred meters in meandering reaches. Deposits of the post-dam flood plain level and the intermediate bench level were sometimes too narrow to transfer from the 1:5,000 aerial photograph scale to the 1:12,000 map scale although they each occurred at most cross sections (Fig. 18). Individual deposits too narrow to map were occasionally grouped. In all cases, if the deposit was partially active, it was labeled an active-channel deposit. Similarly, if an area too small to map as two units was part post-dam flood plain and part intermediate bench, it was labeled post-dam flood plain. Some intermediate bench deposits too small to map separately were included with c-b terrace deposits.

Depositional Environment of Deposits

The depositional environment of alluvial deposits represented in Lodore Canyon, Whirlpool Canyon, and Split Mountain Canyon include channel-margin deposits, eddy bars, expansion bars, and point bars (Fig. 22). Meandering reaches contain mid-channel islands, point bars, and channel-margin deposits. The characteristics of these depositional environments are discussed in more detail in Chapter 2. Deposits of each depositional environment occur at each of the four geomorphic levels discussed above.

Analysis of Historical Changes

Summary of Historical Photographs

Comparison of historical aerial and oblique photographs with present conditions permits an analysis of the effects of climatic and dam-induced changes on the size and distribution of alluvial landforms in the study area. These comparisons show that the channel has narrowed throughout the study area and that the size of active expansion bars and eddy bars has greatly decreased in Lodore Canyon. The following sections describe the style of these changes, and the subsequent section examines systemwide changes based on analysis of GIS map data.

Observations made from historical photographs were categorized and tabulated (Appendix C) and are summarized in Table 7. Eighty-six percent of the photo-replicates show that riparian vegetation is more abundant now than it was between 1871 and 1922. Most of the new plants are tamarisk or ground-cover species. Aggradation of fine-grained alluvium was documented by the 16 percent of the photo-replicates that showed gravel in the original photograph and fine-grained sediment in the same location in the recent photograph. A decrease in bankfull channel width occurred in 53 percent of the photo-replicates. Erosion of the c-b terrace was recorded in five photo-replicates of meandering reaches where the position of the cutbank could be determined in reference to stable features such as trees and the alluvium-bedrock contact.

Lodore Canyon. Active gravel bars are smaller and eddy sand bars are smaller and occur at lower elevations than in 1871, 1895, 1909, or 1922. These trends were determined by matching 32 photographs in Lodore Canyon. Elements of fan-eddy complexes are shown in 15 photographs, 6 of which depict the debris fan. No changes in morphology have occurred at these fans, indicating that debris flows have not occurred at any of these sites within the past century. Five of the 15 photographs show gravel bars and in every case, these bars are covered by 30 to 60 cm of fine-grained sediment that was not present in the original photograph. Four of the 15 photographs show eddy bars, and these bars are now mostly or partly covered by vegetation which obscures topography and reduces the size of the active bar. Fourteen of the photographs depict channel-margin deposits, all of these except one showing channel narrowing and more geomorphic surfaces today than in 1871, 1895, 1909, or 1922. One of the photographs of channel-margin deposits and three photographs of rapids show no change. Thus the coarsest elements of the bed, the boulders that occur in rapids, have been stable since 1871.

The style of change in eddy bars is illustrated by matched photography at a site located about 3.7 km downstream from the Gates of Lodore (Fig. 23). The open sand bar in the 1871 photograph is an example of a typical reattachment bar and the deep channel in the foreground is a return-current channel. These types of deposits have been described in Grand Canyon by Schmidt (1990), Rubin and others (1990), and in Lodore Canyon in Chapter 2 of this report. The large upstream-projecting spit of the bar no longer exists and the return channel is now filled with sand. The elevation of the surface of the original sand bar is about the same as that of the intermediate bench level and is now overgrown by tamarisk. Topographic surveys and stratigraphic analysis at this site show that four geomorphic levels now occur (Fig. 24). Presently, the active sand bar is much smaller, is about 2 m lower in elevation, and does not have the same eddy-bar morphology. The intermediate bench deposits are inset into the c-b terrace, consistent with observations elsewhere.

A tamarisk was excavated at this site and ages of the trunk above root crowns show that the intermediate bench has formed since completion of Flaming Gorge Dam. Root crowns were identified at 30 and 80 cm depth below the surface (Fig. 24). Tree-ring counts indicate that the tree began growing from the 30 cm root crown in about 1973 and germinated from the 80 cm root crown in about 1965. These ages indicate at least two depositional events have occurred in the past 31 yr at this surface, both of which pre-date the 1983 flood that would have inundated the intermediate bench. Measurements of water surface elevations during this study at this site show that the intermediate bench level is not inundated by maximum power plant releases of 122 m^3s^{-1}, but that such flows would have covered the bar when its upper surface was at the level of the root crowns of the excavated tamarisk tree. Thus, normal power plant releases, and especially a slightly higher release of 140 m^3s^{-1} that occurred in 1972 must have constructed the 50 cm thick sequence between the two root crowns. The upper 30 cm of the deposit was probably initially deposited by the 146 m^3s^{-1} high flow in 1975 and aggraded to its present elevation by the higher flows of 1983, 1984, and 1986.

Vertical aggradation of fine-grained alluvium on formerly active gravel bars is illustrated by the matched photographs at Lower Disaster Falls, Rkm 569.5 (Fig. 25). The gravel bar and a downstream debris fan constrict flow against a bedrock wall on river right, resulting in the well-known rapid. Much of this gravel bar is now covered by up to 1.0 m of sand that has accumulated since 1922. Topographic mapping and stratigraphic analysis show that about 120 m^3 of fine-grained aggradation has occurred on top of the gravel bar (Fig. 26).

Echo Park. Geomorphic change at Echo Park was analyzed by the use of historical aerial and oblique photography and repeat topographic surveys. This area is also the site of important cultural resources and a National Park Service campground. An increase in vegetation cover indicating the establishment of the new flood plain is shown in each of the four oblique photographs replicated in this reach. Two of these photographs also show a narrowing of the active channel and erosion of the alluvial terrace. These changes are illustrated by photographs showing Echo Park in 1917 and 1995 (Fig. 27). The large sandbar in the foreground is about the same size in each photo and gives the impression of little change. However, the increase in vegetation and the establishment of a new flood plain are shown in the background on river left where there is a large tamarisk grove in 1995 separating the active channel from the c-b terrace. Erosion of the terrace has occurred on river right adjacent to the small hill in the foreground of the photographs. This area was stable between 1954 and 1993 and thus the erosion shown occurred between 1917 and 1954.

A surficial geologic map of Echo Park was made from 1954 aerial photography and compared with field mapping done in 1993. Active channel deposits, c-b terrace, small deposits of intermediate bench, and water surface were identified in the 1954 photographs and mapped. The intermediate bench interpreted from the 1954 photographs is vegetated and located at a lower elevation than the c-b terrace. This level appears similar to the level mapped as the intermediate bench in 1993 but is less extensive in area. The bankfull channel is the sum of the water surface and all active alluvial deposits (Table 8). The area of the bankfull channel has decreased by about 13 percent, resulting in about 8 hectares of channel narrowing over a 4.6 km reach. This narrowing has occurred by a 6 hectare increase in the area of the intermediate bench and the establishment of 1 hectare of post-dam flood plain. One hectare of decrease in bankfull channel area is unaccounted for. Some erosion of the c-b terrace has occurred and is concentrated at the Echo Park campground. The terrace on river right on the west side of Steamboat Rock was stable (Fig. 27) and the terrace on river left in Mitten Park was only slightly reduced in area. As the size of the terrace has been reduced, the area of active deposits exposed at low discharge has increased in the area of the campground.

Recent erosion of the terrace at the Echo Park campground is documented by resurveyed channel cross sections. A total of 6 m of cutbank retreat occurred at section 33 between July 1994 and June 1996. Most of this erosion occurred between August 1995 and May 1996. The cutbank at section 34, similar in height to the one at section 33, was completely stable for the entire period. Observations made during peak flows indicate that the sandbar adjacent to the cutbank directs the thalweg towards the center of the channel, whereas at cross-section 33 the mid-channel bar directs the thalweg towards the left bank where cutbank erosion occurs.

Whirlpool Canyon. Fewer historical photographs exist for Whirlpool Canyon and only two were located and replicated in this study. Figure 28 is a photograph looking downstream in the lower half of Whirlpool Canyon, which shows gravel bars that have not changed noticeably and have not accumulated a veneer of fine-grained sediment. There have been small increases in riparian vegetation along the channel margins. Channel narrowing is, however, indicated by the presence of deposits that are similar to deposits in other reaches that photographic replications show have narrowed.

Island Park. Each of eight matched oblique photographs in the Island Park reach shows an increase in riparian vegetation and a majority of photographs demonstrate channel narrowing and the development of a post-dam flood plain. These changes are illustrated at a site about 1 km upstream from Split Mountain Canyon where a large open sand bar in 1922 is now stabilized by tamarisk and is at an elevation about 2 m above the present active sand bar (Fig. 29). A photo-replication that includes most of Island Park shows channel narrowing by the accretion of mid-channel bars to adjacent terraces (Fig. 30). The intermediate bench is not present in any of the old photographs from 1922 or earlier.

The spatial extent of changes in Island Park was measured by comparing surficial geologic maps made from 1938 aerial photographs with maps made from 1993 photographs. Active channel deposits, c-b terrace, small deposits of intermediate bench, and water surface were identified in the 1938 photographs and mapped. The intermediate bench interpreted from the 1938 photographs is vegetated and located at a lower elevation than the c-b terrace. This level appears similar to the level mapped as the intermediate bench in 1993 but is less extensive in area. The bankfull channel is the sum of the water surface and all active alluvial deposits (Table 9). Comparison between 1938 and 1993 shows that there has been a 25 percent decrease in bankfull channel area. This increase in area has occurred by a 10 hectare increase in the area of intermediate bench, a 15 hectare increase in the area of the c-b terrace, and the creation of 30 hectares of post-dam flood plain.

Split Mountain Canyon. The photographic comparisons made for Split Mountain Canyon resemble those made for Whirlpool Canyon. Six of the 11 photographs matched show gravel bars and one shows a debris fan. Three of these six show increase in riparian vegetation but none of these show accumulations of fine-grained alluvium. Increases in riparian vegetation and channel narrowing are, however, shown in the four photographs that include eddy bars or channel-margin bars. This style of change is illustrated by the matched photographs in Figure 31, which depict a large sand bar in the eddy below Inglesby Rapids at about Rkm 512.7 in Split Mountain Canyon. Channel narrowing is shown by the establishment of vegetation on the post-dam flood plain and intermediate bench geomorphic surfaces. Active channel deposits and the c-b terrace are still present.

Distribution of Geomorphic Surfaces and Channel Narrowing

The number and area per-km of each of the mapped geomorphic levels within each reach was calculated (Table 10). Meandering reaches contain about one order of magnitude more alluvium per km than do canyon reaches. The c-b terrace accounts for the greatest percentage of alluvium in all reaches except Whirlpool Canyon where active channel deposits cover the largest proportion of the valley. The active channel deposits are the second most abundant geomorphic level in the Echo Park, Island Park, and Split Mountain Canyon reaches. The intermediate bench is the second most abundant level in Lodore Canyon but is rare in all other reaches. In general, most of the active channel deposits and the c-b terrace geomorphic levels are located in the reaches below the Yampa River confluence while the post-dam flood plain and the intermediate bench levels are concentrated in Lodore Canyon.

The relative abundance of the different geomorphic levels also differs by depositional environment and subreach. The four geomorphic levels were grouped into three levels to simplify comparison between depositional environment categories. Channel-margin bars and island bars are the primary form of the c-b terrace level in all reaches (Table 10). Point bars are the most common form of active deposits in Echo Park, Island Park, and Split Mountain Canyon. They are also the most common form of the cb-terrace in Lodore Canyon and the flood plain-intermediate bench levels in Whirlpool Canyon. Expansion bars are the most abundant depositional environment in the post-dam flood plain and intermediate bench level in Lodore Canyon, as well as in active-channel level in Whirlpool Canyon, and the c-b terrace level in Split Mountain Canyon. Eddy bars typically occur at the post-dam flood plain and intermediate bench levels in Lodore Canyon and Whirlpool Canyon, and at the active-channel level in Split Mountain Canyon. Eddy bars are rare in Island Park and Echo Park.

The degree of channel narrowing that has occurred throughout the study area was estimated by using the surficial geologic map data in conjunction with the historical photograph results. The historical photographic replications and analysis of aerial photography demonstrate that the style of channel change is consistent within each geomorphic subreach. Additionally, field mapping shows that the present geomorphic levels are correlative through the entire study reach. It is therefore reasonable to extrapolate data about historical changes based on photographic analysis to the entire study area. The present planform area of bankfull channel, as determined from the map data, is the sum of the water surface area and all active channel deposits. The area of the pre-dam bankfull channel is calculated as the sum of the present bankfull channel, the post-dam flood plain, and the intermediate bench. Both the post-dam flood plain and the intermediate bench are shown in the oblique photographs taken before 1922 to be mostly active channel deposits with sparse vegetation cover and are therefore considered part of the pre-dam bankfull channel.

Averaged for the study area, bankfull channel width decreased by about 20 percent. The highest decrease in average width is in Island Park where the current bankfull channel is 75 percent that of the pre-dam bankfull channel (Table 11). The narrowing has been slightly less in Lodore Canyon where the current bankfull channel is 78 percent of the pre-dam bankfull channel area. In the other debris fan-dominated canyons downstream from the Yampa River confluence, narrowing has been less than in the Lodore Canyon reach upstream.

Channel narrowing has occurred by new deposition of several facies, which vary in importance depending on subreach (Table 12). Most narrowing in debris fan-dominated canyons occurred within fan-eddy complexes. Decrease in the area of active eddy bars caused 33 percent of the narrowing in Lodore Canyon, and decreased area of active expansion bars caused an additional 29 percent of the total narrowing. Eddy bars caused 52 percent of the narrowing in Whirlpool Canyon, but expansion bars caused 79 percent of the narrowing in Split Mountain Canyon. Deposition of new channel-margin and mid-channel bars caused nearly all of the narrowing in meandering reaches.

Estimates of Gravel Mobility

In an effort to determine why gravel bars in Lodore Canyon are no longer active, average boundary shear stress was estimated at selected channel cross sections. The shear stresses generated by rare floods that inundate the c-b terrace are compared with those generated by common floods that inundate the post-dam flood plain. These levels were chosen for the comparison because they can be identified at most cross sections in the study area and because the discharges that inundated these features represent elements of the pre- and post-dam flow regimes. The discharge required to inundate the c-b terrace is in the range of the pre-dam 25-yr flood. The post-dam flood plain is inundated by approximately the post-dam 2-yr flood both upstream and downstream from the Yampa River confluence. Shear stress was estimated from the product of the specific weight of water γ, the mean depth D and the water-surface slope S,

$$\tau = \gamma DS. \tag{3}$$

Even in the relatively deep and narrow channel in the canyon reaches, hydraulic radius is well approximated by mean depth, which was used in the calculations. Boundary shear stress was compared with estimates of critical shear stress for median particle size of each gravel bar. A first-order approximation of flows necessary to mobilize the gravel bars was made by estimating critical shear stress using the Shields relation (Shields, 1936):

$$\tau_{c50} = \tau^*_{c50}(\gamma_s - \gamma_f)D_{50}, \tag{4}$$

where τ_{c50} is the critical shear stress for the median particle diameter of the bed surface in Nm^{-2}, τ^*_{c50} is the critical dimensionless shear stress for the median particle diameter of the bed surface, γ_s is the specific weight of the solid in Nm^{-3}, γ_f is the specific weight of water in Nm^{-3}, and D_{50} is the median particle diameter of each sampled bar, in m. Values for τ^*_{c50} have been found to range over an order of magnitude and are affected by the bed-material size distribution (Andrews, 1983). For this approximation we used 0.033, the value found by Andrews (1983) to be the most common for coarse-bedded streams.

Figure 32 shows the downstream variation in critical shear stress necessary to entrain the median particle size of each gravel bar and the estimated average boundary shear stress at each cross section. The average boundary shear stress and the critical shear stress are larger in canyon reaches than in meandering reaches. Bed material size is, on an order of magnitude scale, in approximate adjustment with shear stresses of the pre-dam era. The calculated shear stresses for the pre-dam 25-yr flood approximate and sometimes exceed the estimates for critical shear stress in both canyon and meandering reaches. The estimates of average boundary shear stress for the post-dam 2-yr flood are much less than the critical shear stress in canyon reaches but are close to critical shear stresses in meandering reaches. Thus, gravel bars in Lodore Canyon are not mobilized by normal power plant operations in the post-dam era.

Calculation of Effective Discharges

An estimate of suspended sediment transport was made for the sand-bedded reach immediately above the entrance to Lodore Canyon. The estimation was made by the Engelund and Hansen (1967) method applicable for sand-bedded channels. Cross-section 6 (Rkm 580.8) was used for the calculation and the local water-surface slope was surveyed in the field. Mean bed-material size was determined from sieve analysis of samples collected from the thalweg of the measured cross section. Sediment transport per unit width of bed was determined as

$$q_T = \Phi\sqrt{(s-1)gd_f^{\,3}}\ , \tag{5}$$

where q_T is sediment transport per unit width of bed, s is the specific gravity of sediment, g is the acceleration due to gravity, and d_f is the particle fall diameter, and Φ is dimensionless sediment transport given by,

$$\Phi = \frac{0.1\theta^{\frac{5}{2}}}{f}, \tag{6}$$

where f is the friction factor determined by,

$$f = \frac{2gDI}{V^2}, \tag{7}$$

and velocity is estimated as,

$$V = \sqrt{gD'I}\left(6.0 + 2.5\ln\frac{D'}{k}\right), \tag{8}$$

given the following definitions,

$$D' = \frac{\theta'}{\theta} D, \tag{9}$$

$$\theta' = 0.06 + 0.4\theta^2, \tag{10}$$

$$\theta = \frac{DI}{(s-1)d_f}, \tag{11}$$

where I is water-surface slope, k is surface roughness (2.5 df), and D is mean depth.

These calculations were used to estimate sediment transport for the measured cross section for mean depths from low to bankfull stage. The discharge and sediment transport per unit width were multiplied by the channel width for the respective mean depth to obtain total discharge, Q, and total sediment transport, Q_{sed}. The resulting sediment rating relation is $Q_{sed} = 9381.719\ Q^{1.702}$.

The sediment rating relation and daily discharge data for the Green River at Greendale, Utah, were used to calculate the quantity of sediment transported by discrete discharge increments. The range of discharges was divided into 42 equal increments between 0 and 600 m^3s^{-1}, each containing 14.3 m^3s^{-1} of discharge. The sediment transport rate was calculated for the discharges at the upper and lower limits of each increment were then averaged to determine the mean load for the increment. The mean load for each increment was then multiplied by the fraction of time streamflow occurred within the limits of the given increment for the time interval of interest. The calculation was repeated for three separate time intervals: 1951 to 1961, which is the pre-dam period; 1961 to 1981, which is the post-dam period without any flows above peak power plant discharge; and 1981 to 1990, which is the post-dam period during which flows did exceed peak power plant discharge. The curves plotted from the results of these calculations are shown in Figure 33. The peak of the sediment transport-discharge product has been termed the effective discharge because it is the discharge range that transports most of the river's sediment load for a given time interval. The pre-dam curve is relatively flat, indicating that a broad range of flows contributed about equally to the total annual sediment load. Both post-dam curves have a large peak just below the peak power plant discharge. This indicates that a major portion of the river's annual sediment load is transported by the peak power plant discharge. The curve for the post-dam period with floods has an additional peak at about 220 m^3s^{-1}.

Adjustability of the Bed in Post-Dam Flow Regime

The channel cross-section surveys were used in Chapter 2 to describe the geomorphic character of each geomorphic subreach. Repeat surveys of selected cross sections were made in 1995 and 1996 to measure changes in sediment storage during the passage of each year's high flows. The area of each channel cross section for each time of measurement was determined in relation to a common reference stage. The cross-sectional areas are normalized by dividing the calculated area by the area of that cross section in 1994 to permit comparisons between large and small channels (Fig. 34). An increase in area indicates erosion and a decrease indicates aggradation. Averaged for the entire study reach, cross-sectional area decreased by about 1 percent in 2 yr. The canyon reaches are on average less adjustable than the meandering reaches, which contain a greater percentage of fine-grained alluvium. Adjustability was calculated as the maximum amount of change (scour or fill) to occur in a given interval. Whirlpool Canyon and Lodore Canyon had an average adjustability of from 2 to 5 percent, compared to 7 and 17 percent for Echo Park and Island Park, respectively. The behavior of the entire study area cannot be characterized by the behavior of any single cross section, however. During any given time interval, some cross sections eroded, some aggraded, while others did not change. Similarly, a single cross section may or may not have responded consistently during time intervals of comparable flow regime.

Nevertheless, the data indicate some trends. In Lodore Canyon, Echo Park, and Whirlpool Canyon, scour tends to occur between May and September while fill tends to occur between August and May (Fig. 35). An exception to this pattern was measured between June and September 1996 when fill occurred in Echo Park and scour occurred in Lodore Canyon and Whirlpool Canyon. In Island Park, scour occurs between September and June and fill occurs between May and September. About 50 percent of the cross sections surveyed more than twice followed the trend of thalweg scour-and-fill (Appendix D). The remainder exhibited either no pattern of change or no change at all.

Although the reach-average change and adjustability are small, one cross section in Island Park increased in area by 37 percent then decreased by 35 percent during the next time interval. Large areas of either erosion or deposition at a single cross section tend to be offset by the opposite response during a subsequent time interval. Thus, the maximum net changes for a single cross section during the study period are a decrease in area by 14 percent and an increase in area by 7 percent. The cross section with the maximum erosion is located in Lodore Canyon and the one of maximum deposition is in Echo Park.

Discussion

Flood plain-like and terrace-like surfaces occur at multiple elevations throughout the study area, which encompasses debris fan-dominated canyons, reaches of restricted meanders, and reaches of incised meanders. The horizontal bedding of the sediments shows deposition by vertical accretion, which has been documented to be the dominant flood plain-forming process in other confined rivers (Nanson, 1986; Schmidt and Rubin, 1995; Hereford and others, 1996). The vertically aggrading landforms that exist along the Green River are also longitudinally correlative, distinguishing them from the vertically aggrading deposits described by Nanson (1986), but consistent with the findings of Hereford and others (1996). The existence of this correlation in a debris fan-dominated canyon with frequent hydrologic controls, and absence of correlation in a canyon without debris fans, suggests that correlation of flood plains depends on the hydrologic regime rather than the physical characteristics of the canyon. While the average gradient and the mean annual flood of Nanson's (1986) study streams in Australia and the Green River are similar, the magnitude of the 20-yr flood is more than twice as large on the Australian coastal streams than on the Green River. Thus, noncorrelative flood plains seem to exist where the flood-frequency relation is steep and correlative flood plains may form in both narrow gorges and meandering reaches when the flood-frequency relation is flat, such as on the Green River and in Grand Canyon.

The c-b terrace, upstream and downstream from the Yampa River confluence, is inundated only by extremely rare floods in the present regime, regardless of regulation by Flaming Gorge Dam. This is consistent with the findings of Mayers and Schmidt (1994), who describe a "cottonwood terrace" immediately downstream from the study reach near Jensen, Utah, that is inundated by flows between 990 m^3s^{-1} and 1,190 m^3s^{-1}. Both the intermediate bench and the post-dam flood plain, however, have been inundated by post-dam floods throughout the entire study reach. The post-dam flood plain is inundated by about 143 m^3s^{-1} and 500 m^3s^{-1}, upstream and downstream from the Yampa River confluence, respectively. Mayers and Schmidt (1994) describe a "post-dam flood plain" near Jensen, Utah, that is inundated by about 622 m^3s^{-1}. Because of the flat flood-frequency relation, the value reported by Mayers and Schmidt (1994) and the value reported in this study both lie between within the range of the 2- to 4-yr flood event. The intermediate bench is not inundated by the mean annual flood either in Lodore Canyon or downstream from the Yampa River confluence. In Lodore Canyon it is inundated by the rare post-dam flood that had a pre-dam recurrence interval of about 3 yr. The pre-dam 3-yr flood downstream from the Yampa River confluence was about 700 m^3s^{-1}, which field evidence indicates to be the discharge at which the intermediate bench is inundated in this reach. Mayers and Schmidt (1994) also describe a surface intermediate in elevation to their cottonwood terrace and post-dam flood plain but do not report an inundation discharge.

Flood-plain elevation has been correlated with the effective discharge on alluvial rivers and on a restricted meander reach of the Yampa River (Andrews, 1980). The stage that inundates the post-dam flood plain in Lodore Canyon corresponds to the post-dam effective discharge for the Green River upstream from the Yampa River confluence. Andrews (1986) calculated effective discharge for the Green River near Jensen, Utah. Although sediment transport-discharge product peaks at about 340 m^3s^{-1}, discharge increments up to about 500 m^3s^{-1} contribute substantially to the annual load. It is therefore likely that the post-dam flood plain downstream from the Yampa River confluence also corresponds to the effective discharge for that reach. One or more of the secondary post-dam peaks for the Green River upstream from the Yampa River above 200 m^3s^{-1} may correspond with the intermediate bench in that reach. However, there are several peaks in the curve, and the stage-to-discharge relationship for the intermediate bench is not precise enough to firmly establish this correlation. Thus, the concept of effective discharge as it applies to frequently occurring flows that transport a large portion of the sediment over period of several years may be applied to explain the development of flood plains in debris fan-dominated canyons. However, not all of the geomorphic surfaces identified in the study area are clearly associated with a peak in the effective discharge curve.

Post-dam deposition has resulted in the formation of multiple geomorphic surfaces. Stratigraphic evidence shows post-1962 deposition at the level of the intermediate bench. This is supported by interpretation from 1954 and earlier photographs that show much less area covered by the intermediate bench than exists now. Similarly, all of the areas that are now post-dam flood plain were active channel in 1954 and earlier photographs, indicating deposition at this level. Some gravel bars have had up to 1 m of fine-grained deposition. These observations conflict with the conventional notion that associates a single flood plain with a single channel-forming discharge but support the findings of Pizzuto (1994) that multiple geomorphic surfaces can form concurrently in response to floods of different magnitudes. Flood plain-like features along the Green River form both during the common discharges of the mean annual flood and during rare floods that have recurrence intervals of about 10 yr, downstream from the Yampa River, or higher as in Lodore Canyon.

The evidence discussed above derived from surficial geologic mapping and interpretation of photographs provides direct evidence of landform change. All pre-dam photographs matched in this study show a wider active channel and less riparian vegetation in the past than exists at present. Two geomorphic surfaces, the post-dam flood plain and the intermediate bench, absent or rare in old photographs, are abundant in recent photographs. The post-dam flood plain did not exist in any of the 1954 or earlier photographs, but is common now. Photographs as old as 1917 show a surface lower in elevation than the c-b terrace that has some riparian vegetation. However, most of the area that is now intermediate bench was active channel in the 1954 and earlier photographs. The degree of channel narrowing ranges from 10 to 25 percent. With the exception of Island Park, the degree of narrowing downstream from the Yampa River was about 50 percent of the narrowing that occurred in Lodore Canyon. The amount of narrowing that occurred in the Echo Park fixed-meander reach is similar to the amount measured in the debris fan-dominated canyons downstream from the Yampa River confluence. The greater degree of narrowing in Lodore Canyon is consistent with greater degree of flood reduction that has occurred upstream from the Yampa River confluence.

The amount of channel narrowing measured in this study is greater than the amount measured by previous studies. Andrews (1986) measured 13 percent decrease in bankfull channel in Brown's Park (immediately upstream from Lodore Canyon) and near Ouray, a reach of restricted meanders about 100 km downstream from the study area, between 1964 and 1978. Lyons and others (1992) reported a similar decrease for the Ouray reach between 1964 and 1974, but measured channel widening between 1974 and 1986, resulting in a 1964 to 1986 decrease of only 7 percent. The channel widening is attributed to the floods that occurred in 1983, 1984, and 1986. The results of this study suggest that channel narrowing has resumed subsequent to the 1980's floods.

Channel narrowing is the expected response in a system in which transport capacity has been reduced while sediment supply has been constant or reduced by a smaller amount (Andrews, 1986). Although sediment budgets predicted that the reaches upstream from the Yampa River should be degrading, photographic and field evidence indicate a depositional regime. Excavations revealed that the intermediate bench geomorphic surface is a deposit inset into the c-b terrace rather than an erosional surface. Moreover, the age of tamarisk root crowns buried in this surface substantiate post-dam deposition. This suggests that the sediment contributions from tributaries in the first 110 km below Flaming Gorge Dam are significant. Because a sediment supply exists and transport capacity is reduced due to the reduction in peak flows, aggradation has occurred.

Reduction in streamflow transport capacity and aggradation is also supported by estimates of shear stress. Comparisons between average boundary shear stress and critical shear stress indicate that flows on the order of the pre-dam 25-yr flood are needed to mobilize gravel bars. Floods on the order of the post-dam mean annual flood are unlikely to mobilize gravel bars, particularly in canyon reaches. This is consistent with the observation that most gravel bars are covered by a veneer of fine sediment that was not present in historic photographs.

Repeat surveys of channel cross sections indicate that the sand-bedded portion of the channel is adjustable by, on average, 7 percent. The meandering reaches are more adjustable than the canyon reaches, and show a small net decrease in area between 1994 and September 1996. The Lodore Canyon cross sections experienced no net change, and the Whirlpool Canyon cross sections exhibited an average of 3 percent increase in cross-sectional area. The general trend exhibited by 46 percent of the cross sections resurveyed indicates scour during the annual flood and fill during the flood recession. This pattern occurs in reaches both upstream and downstream from the Yampa River confluence. The fact that the bed of the Green River is adjustable is important because it is an indication of the general availability of fine-grained sediment in the system. The high degree of adjustability shows that fine-grained sediment is frequently mobilized. Moreover, the study-area-wide trend of slight aggradation shows that fine-grained alluvium is not in deficit and that aggradation and channel narrowing may still be occurring.

The fluvial landforms described in this study are also physical resources of the Green River corridor within Dinosaur National Monument. The above interpretation of recent landform changes and estimations of discharges of inundation may be used in management decisions regarding dam operations with respect to resource management.

Table 13 summarizes the geomorphic features mapped in this study in relationship to physical park resources, inundation discharges, observed changes, and possible effects of floods on the resources. Aggradation and stabilization of active channel deposits to form the intermediate bench and the post-dam flood plain have occurred, resulting in decreased area of bare sand and gravel bars. Similar features in other reaches of the Green River provide habitat for endangered fish. The importance of this reduced habitat within the study area is not known. However, these new flood plain-like features provide habitat for riparian vegetation that supports a new terrestrial biological community. Flows greater than about 240 m^3s^{-1} upstream from the Yampa River confluence and greater than 600 m^3s^{-1} downstream will inundate the post-dam flood plain. The recent channel narrowing and the adjustability of the bed at the measured channel cross sections indicate fine-grained alluvium is abundant in the channel. Thus, aggradation on the post-dam flood plain is likely to occur, possibly following local scour. The initial result will be an increase in the area of active channel deposits, including bare sand and gravel bars. However, rapid establishment of new riparian vegetation, especially tamarisk, may also occur and would depend on the timing of the flood, seed availability, and the post-flood hydrograph. The intermediate bench is a surface that has been stabilized and the present trend is maturation of the riparian plant community. The high flows described above would inundate this surface but probably not to sufficient depth to scour the well-established riparian plants. The flood-tolerant tamarisk, willow, and cottonwood would increase roughness, reduce velocities, and cause aggradation. Higher flows may result in more local scouring. These flows would not be great enough to affect the surface of the c-b terrace. However, local erosion of the terrace, such as has occurred in Echo Park, may occur under any hydrologic scenario.

TABLE 7. SUMMARY OF HISTORICAL PHOTOGRAPH DATA

Reach	Photos replicated	Increase in vegetation	New sand over gravel	Increased geomorphic levels	Erosion of high terrace	No change
		number of photographs that show indicated change				
Lodore Can.	32	27	5	18	0	6
Echo Park	4	4	0	2	3	0
Whirlpool Can.	2	2	0	1	0	0
Island Park	8	8	3	5	2	0
Split Mtn. Can.	11	8	0	4	0	3
Study Area	57	49	8	30	5	9
Percent*		86	14	53	9	16

* Percent of photographs that show indicated change for entire study area.

TABLE 8. BANKFULL- AND ACTIVE CHANNEL AREA IN ECHO PARK IN 1954 AND 1993

Feature	Area, in hectares* 1954	1993	change	percent change
Water surface	34	27	-7	-21
Active-channel deposits	28	27	-1	-4
Post-dam flood plain	0	1	+1	na
Intermediate bench	0†	6	6	na
C-b terrace	35	34	-1	-3
Bankfull channel	62	54	-8	-13

* Area in hectares over a 4.6 km reach.

† The area of intermediate bench in 1954 was < 5000 m^2.

TABLE 9. BANKFULL- AND ACTIVE-CHANNEL AREA IN ISLAND PARK IN 1938 AND 1993

Feature	Area, in hectares* 1938	1993	change	percent change
Water surface	140	115	-25	-18
Active-channel deposits	80	55	-25	-31
Post-dam flood plain	0	30	+30	na
Intermediate bench	25	35	+10	+40
C-b terrace	200	215	+15	+8
Bankfull channel	220	165	-55	-25

* Area is in hectares over a 10.0 km reach.

TABLE 10. AREA OF GEOMORPHIC SURFACES BY REACH AND DEPOSITIONAL ENVIRONMENT

Deposional environment	Level	Lodore Canyon	Echo Park	Whirlpool Canyon	Island Park	Split Mt Canyon
		Area, in thousand square meters per km				
Channel-margin bars	Active	1	51	1	0	0
	P-d fp*	2	2	1	0	0
	Int. b†	2	15	1	0	0
	Terrace	9	105	3	0	1
Mid-channel bars	Active	0	0	0	20	0
	P-d fp	0	0	0	25	0
	Int. b	0	0	0	40	0
	Terrace	0	0	0	178	0
Point bars	Active	0	55	1	2	2
	P-d fp	1	1	1	0	0
	Int. b	1	2	1	0	1
	Terrace	2	6	0	0	0
Expansion bars	Active	1	0	6	0	4
	P-d fp	2	0	1	0	2
	Int. b	3	0	0	0	5
	Terrace	2	0	0	0	13
Eddy bars	Active	1	2	4	0	2
	P-d fp	2	0	1	0	0
	Int. b	3	1	3	0	1
	Terrace	3	1	3	0	1

* Post-dam flood plain.

† Intermediate bench.

TABLE 11. REACH-AVERAGE SUMMARY OF GIS DATA FROM GEOMORPHIC MAPS

Feature	Lodore Canyon	Echo Park	Whirlpool Canyon	Island Park	Split Mtn. Canyon	Total
	Area of each feature, in thousand square meters per kilometer					
Water surface	52	96	51	117	60	67
Active-channel deposits	3	108	12	46	8	19
Post-dam flood plain	8	3	5	27	7	10
Intermediate bench	8	18	3	28	3	10
C-b terrace	16	112	7	189	15	49
Alluvial Valley	88	337	79	407	93	155
Pre-dam bankfull	72	225	72	218	77	106
Post-dam bankfull	56	203	64	163	68	85
Percent change*	-22	-10	-11	-25	-12	-20

*Percent change in bankfull channel width from pre-dam to post-dam, interpreted from geomorphic maps.

TABLE 12. PERCENT OF CHANNEL NARROWING THAT OCCURRED IN EACH DEPOSITIONAL ENVIRONMENT

Feature	Lodore Canyon	Echo Park	Whirlpool Canyon	Island Park	Split Mtn. Canyon	Total
Channel margin	26	80	15	1	1	23
Mid channel	0	0	0	99	0	63
Point bars	11	15	24	0	8	7
Expansion bars	29	0	9	0	79	3
Eddy bars	33	5	52	0	11	3

TABLE 13. RELATIONSHIP OF GEOMORPHIC SURFACES AND RESOURCES TO STREAMFLOW CONDITIONS

Geomorphic surface	Recource	Inundation discharge* (m^3s^{-1})	Changes observed from photo replications	Anticipated effect of high flows†
C-b terrace	• cottonwood and box elder community • NPS facilities and campsites	510 / 1100	• local erosion of terrace in Echo Park and Island Park • no change in vegetation • rare flooding	• cutbank erosion and possible local aggradation on surface
Intermediate bench	• riparian vegetation community	240-388 / 600-1000	• new inset feature • channel-narrowing deposits	• continued aggradation in areas of established vegetation
Post-dam flood plain	• new riparian vegetation community	143 / 455	• channel-narrowing deposits	• scour and fill • return to active channnel
Active deposits	• bare sand and gravel bars • fish habitat • campsites	< 143 / < 455	• less abundant due to channel narrowing	• scour and fill • likely increase in abundance

* Values are for upstream from the Yampa River confluence and downstream, respectively.

† Discharges greater than about 240 m^3s^{-1} upstream from the Yampa River confluence and 700 m^3s^{-1} downstream.

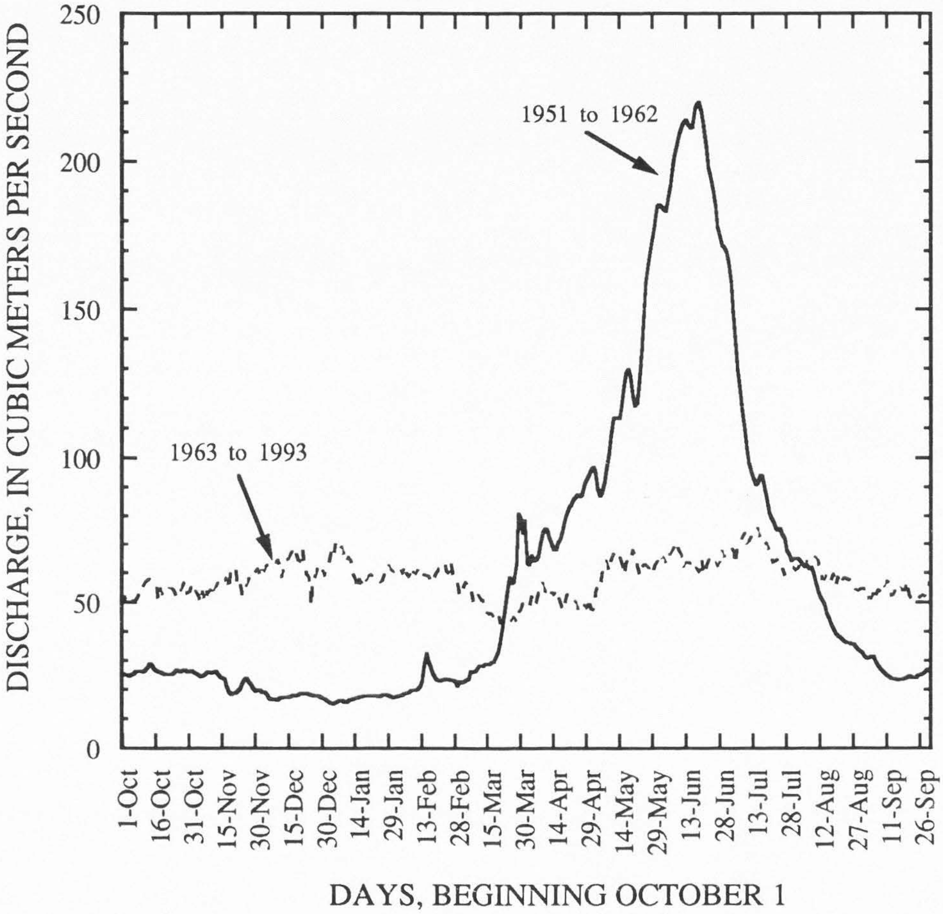


Figure 15. Annual hydrographs of the Green River near Greendale, Utah, comparing average pre- and post-regulation daily mean discharges. The pre-dam peak is much higher and of shorter duration than the post-dam peak. Base flows in the post-dam year are higher during the winter months.

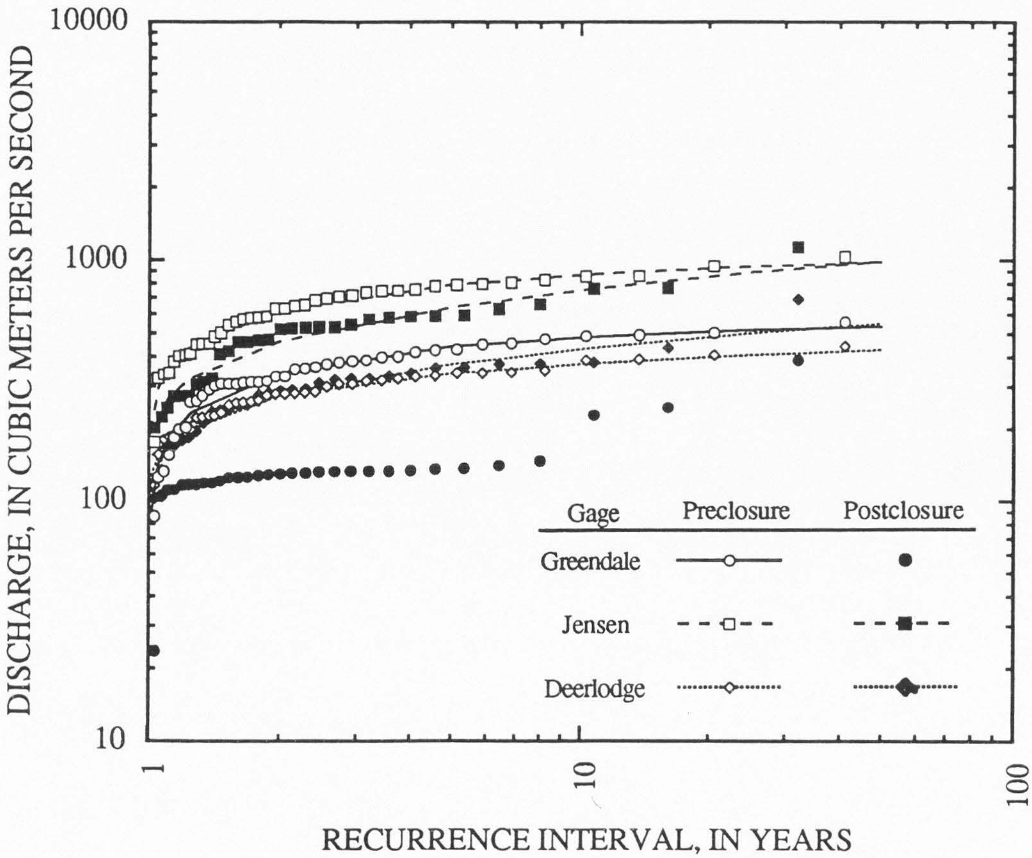


Figure 16. Plot showing annual flood recurrence intervals for the Green River near Greendale and Jensen, Utah, and for the Yampa River near Deerlodge Park, Colorado. Curve fits are log-Pearson type 3.

Figure 17. Photograph looking downstream in Lodore Canyon at three geomorphic surfaces. Flow is 122 m^3s^{-1}, which is peak power-plant discharge. The c-b terrace is located at right and has large box elder trees on its surface. The intermediate bench is the sandy surface in the center of the photograph and has tamarisk trees on its surface. The post-dam flood plain is the submerged grass-covered area downstream from the boat.

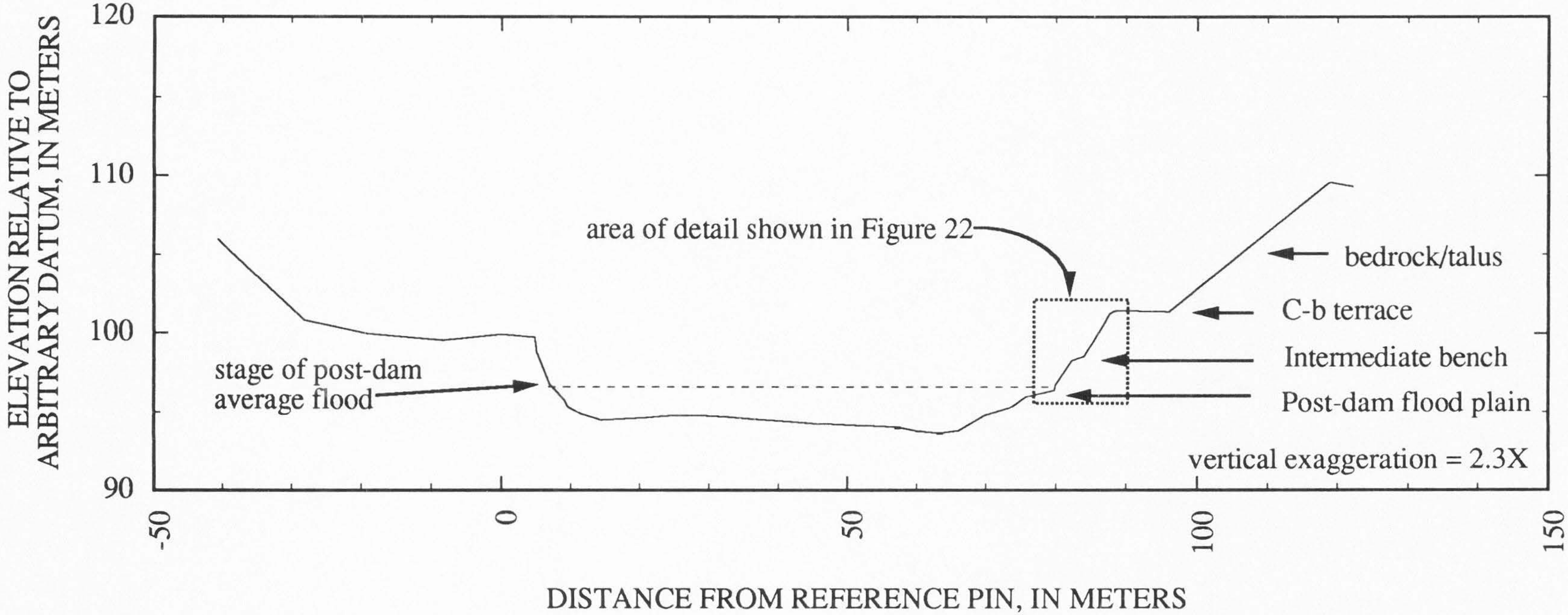


Figure 18. Example channel cross-section showing three geomorphic surfaces. View is downstream at Rkm 574.26 in Lodore Canyon. All surfaces are fine-grained sediments, and the bed of the river is sand.

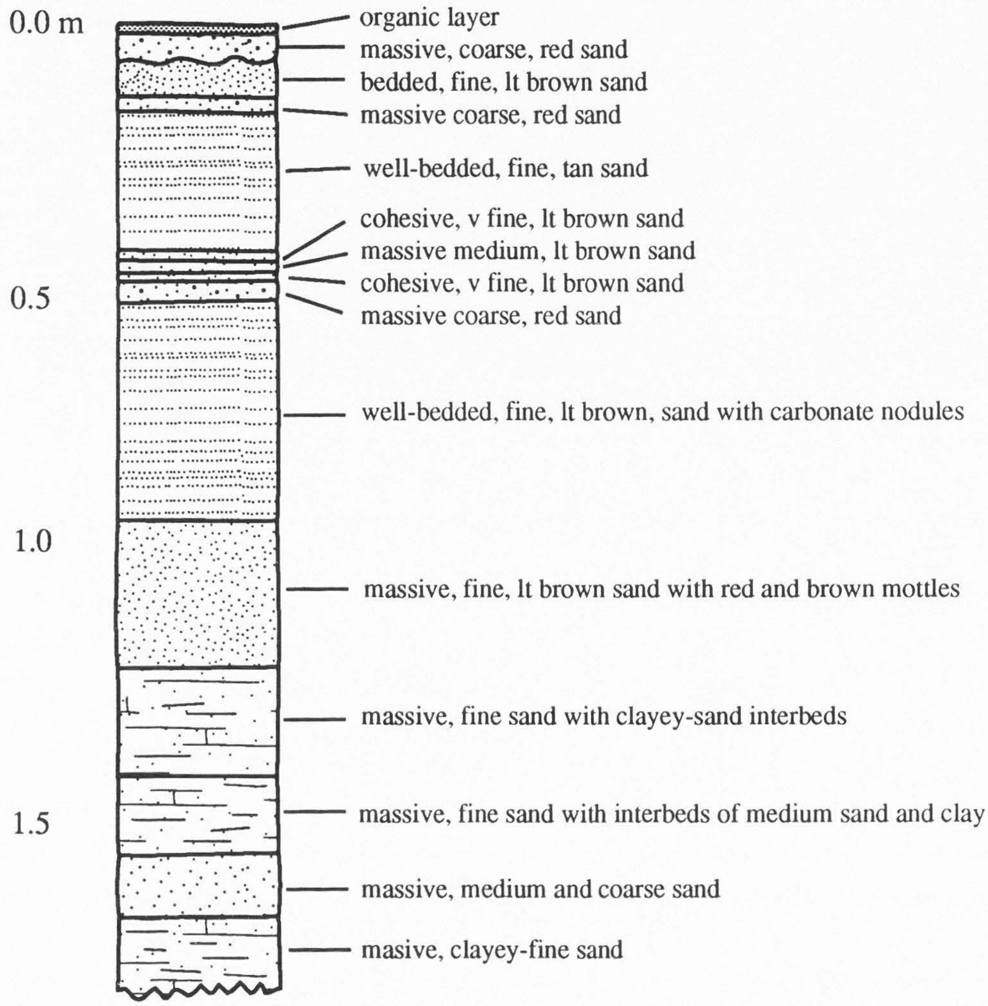


Figure 19. Stratigraphic column of typical c-b terrace exposure located at Rkm 560.0 river right in Lodore Canyon. The several distinct depositional units and common horizontal bedding show deposition by vertical accretion.

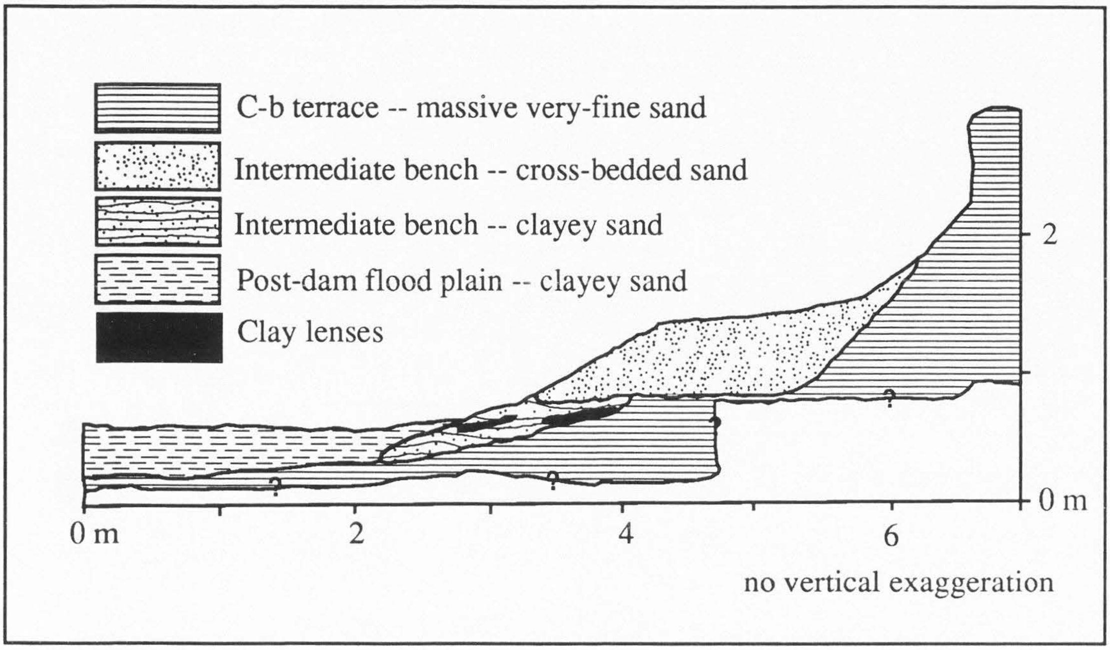


Figure 20. Trench showing intermediate bench geomorphic surface inset into the c-b terrace and the post-dam flood plain inset into the intermediate bench. This is a detail of a segment of the cross section shown in Figure 20. The question marks show the bottom of the excavated trench.

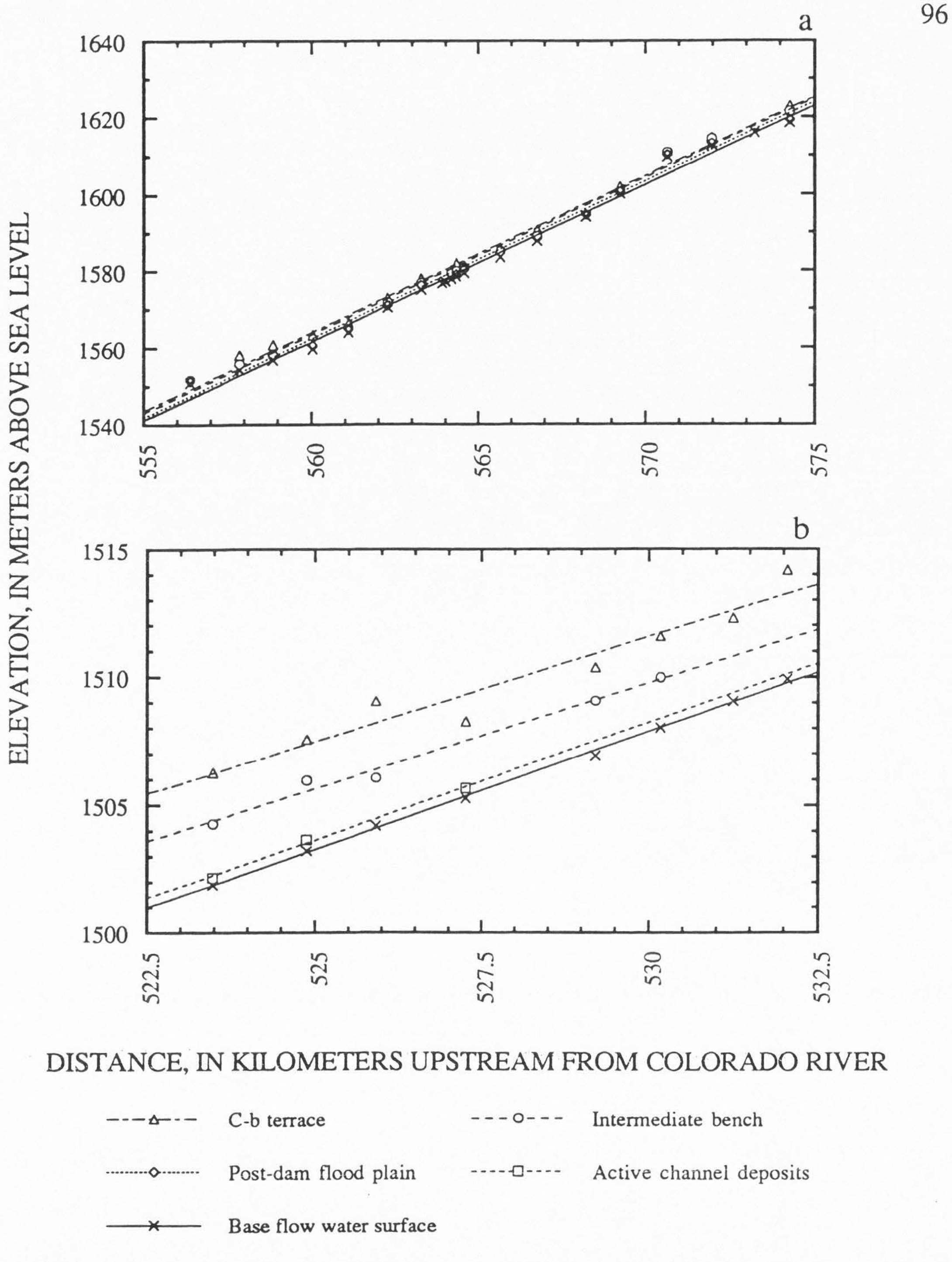


Figure 21. Longitudinal correlation of geomorphic surfaces from Rkm 555 to 575 in Lodore Canyon (a) and from Rkm 522.5 to 532.5 in Island Park (b). Elevations of geomorphic surfaces above baseflow stage are connected by simple regression. The coefficients of correlation are all greater than 0.93 in the Island Park reach and greater than 0.99 in the Lodore Canyon reach. The water-surface elevations are interpolated for each cross-section location from the U. S. Geological Survey (1922) longitudinal profile.

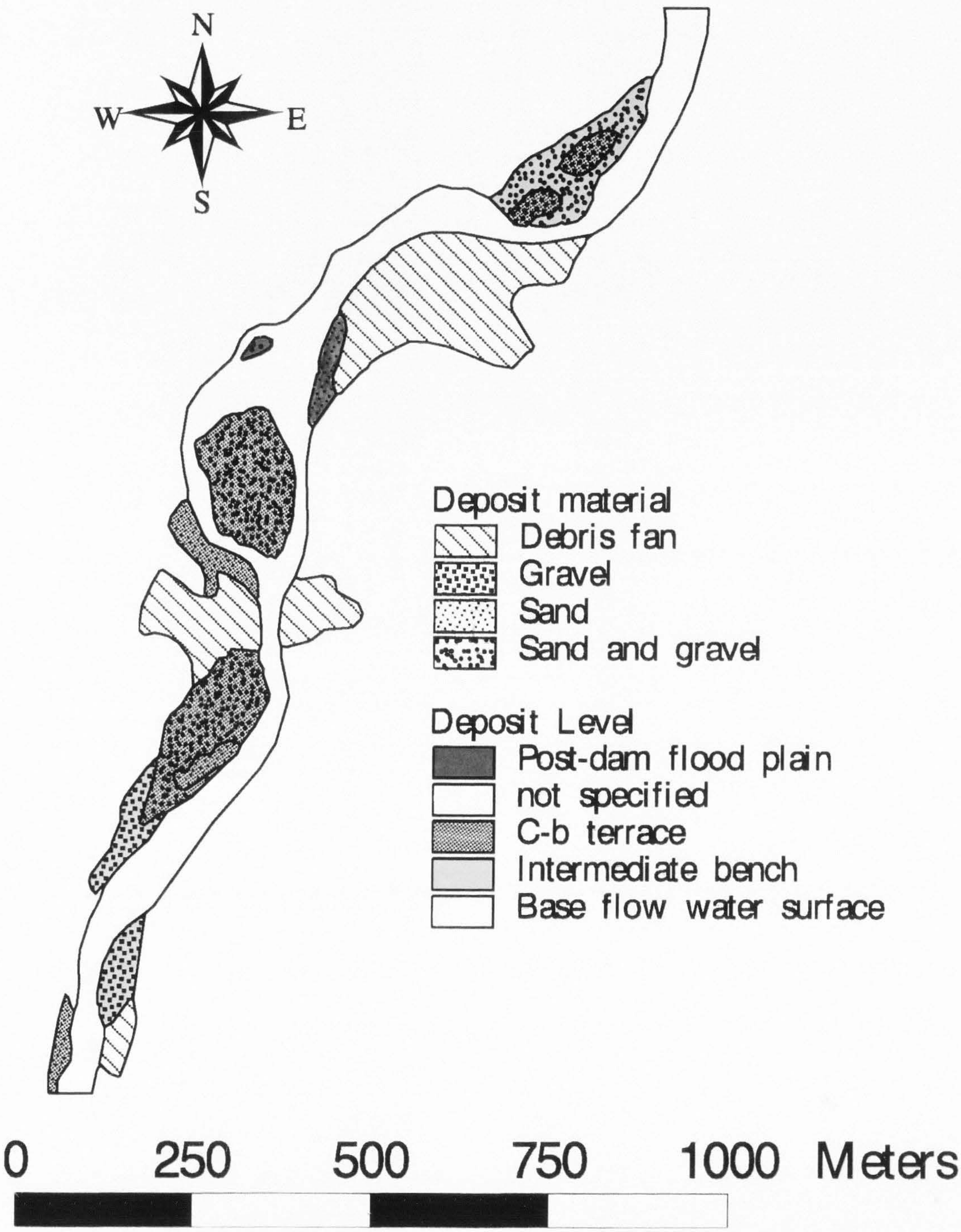
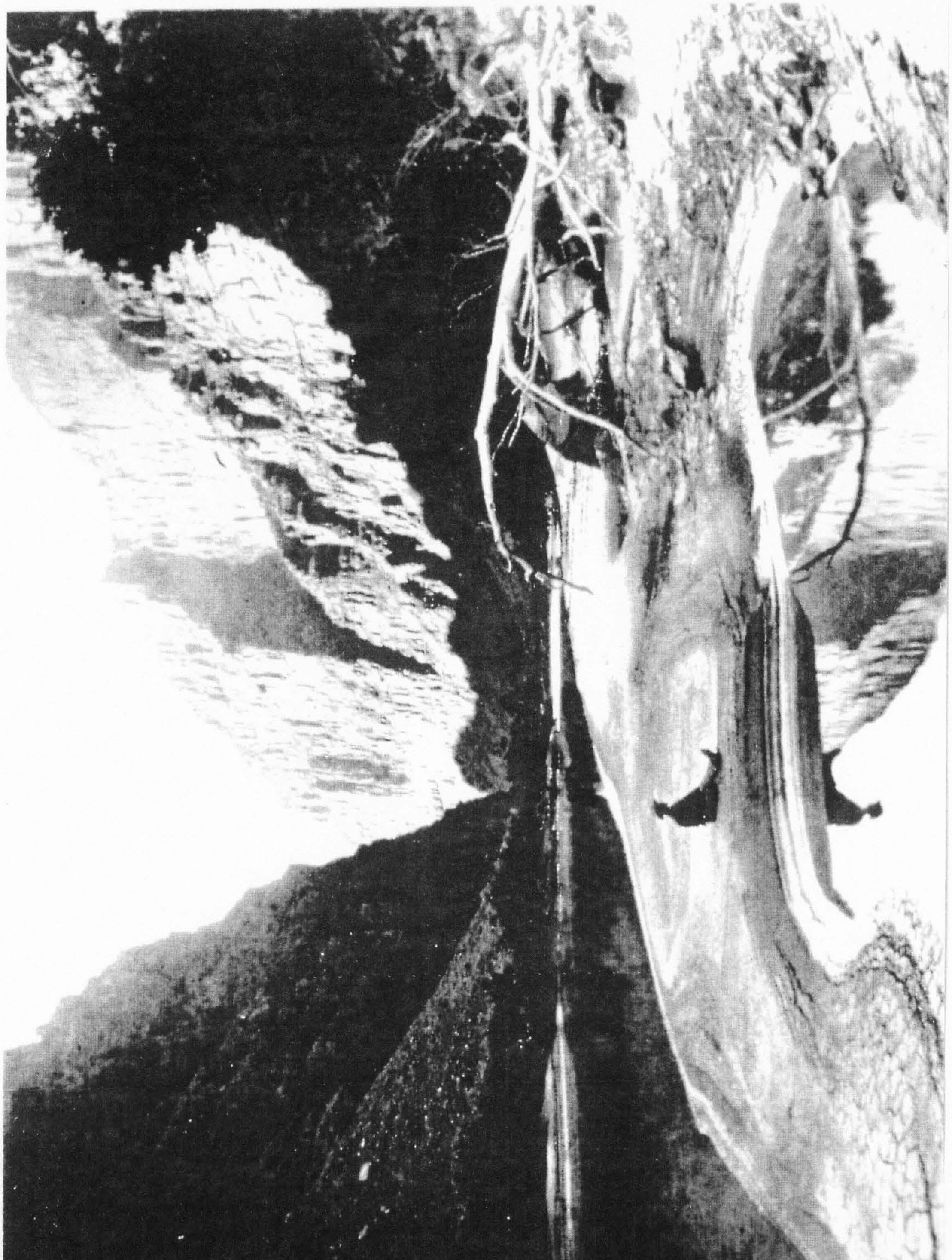


Figure 22. Surficial geologic map of reach in Lodore Canyon beginning at Rkm 568.5. Streamflow is from north to south. Deposit level is indicated by color according to the legend.

Figure 23. Photograph taken June 17, 1871 by E. O. Beaman on the John Wesley Powell expedition (a) and match taken August 22, 1993 (b) of looking downstream in Lodore Canyon from Rkm 577.1. Frederick Dellenbaugh is sitting on the upstream-projecting spit of a reattachment bar. The return-current channel in foreground is now filled and is the level of the intermediate bench and has tamarisk trees on its surface. The large rock in the original photograph is still present and is located immediately to the right of the person in the matched photograph. The cross section shown in Figure 12 extends from right to left through the foreground.


a


b

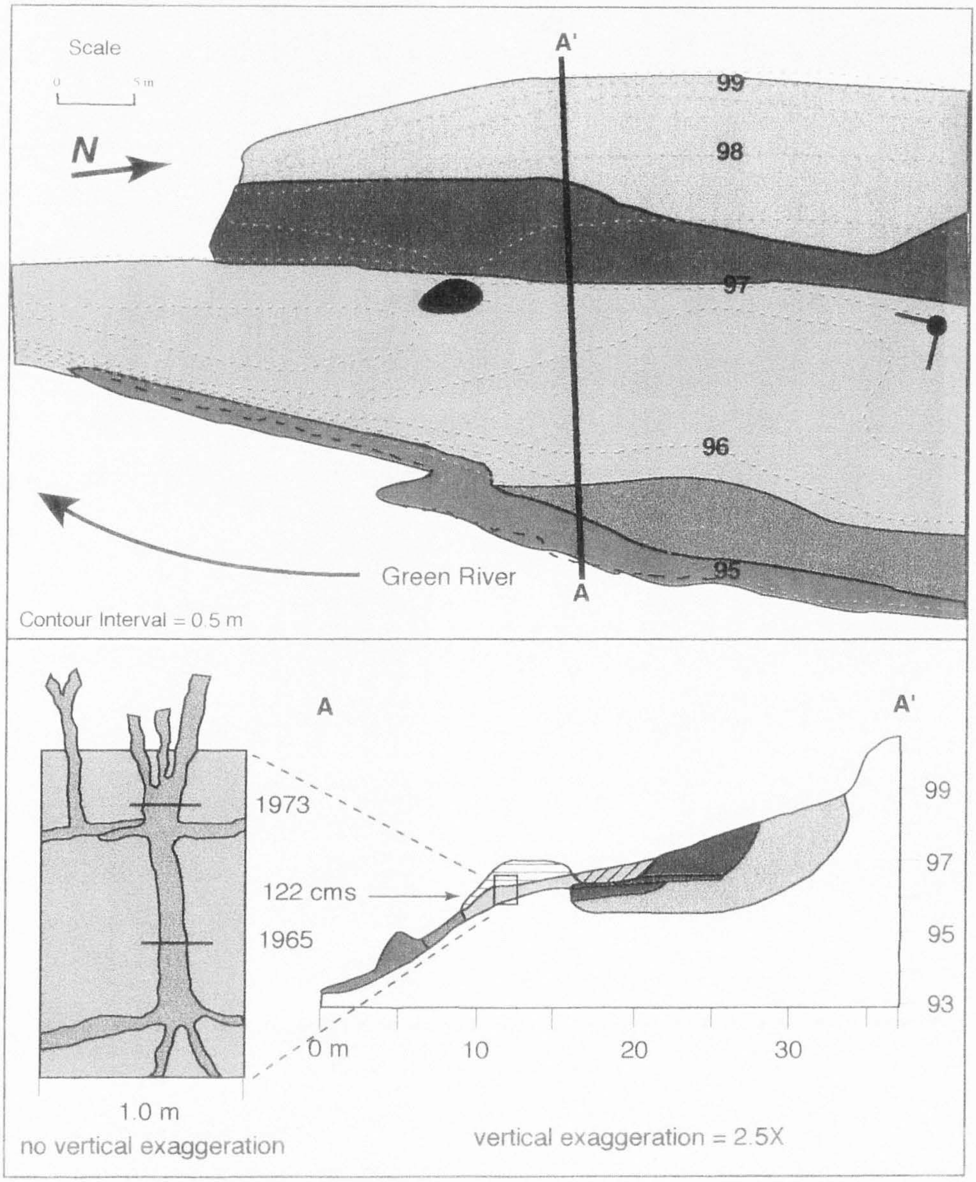
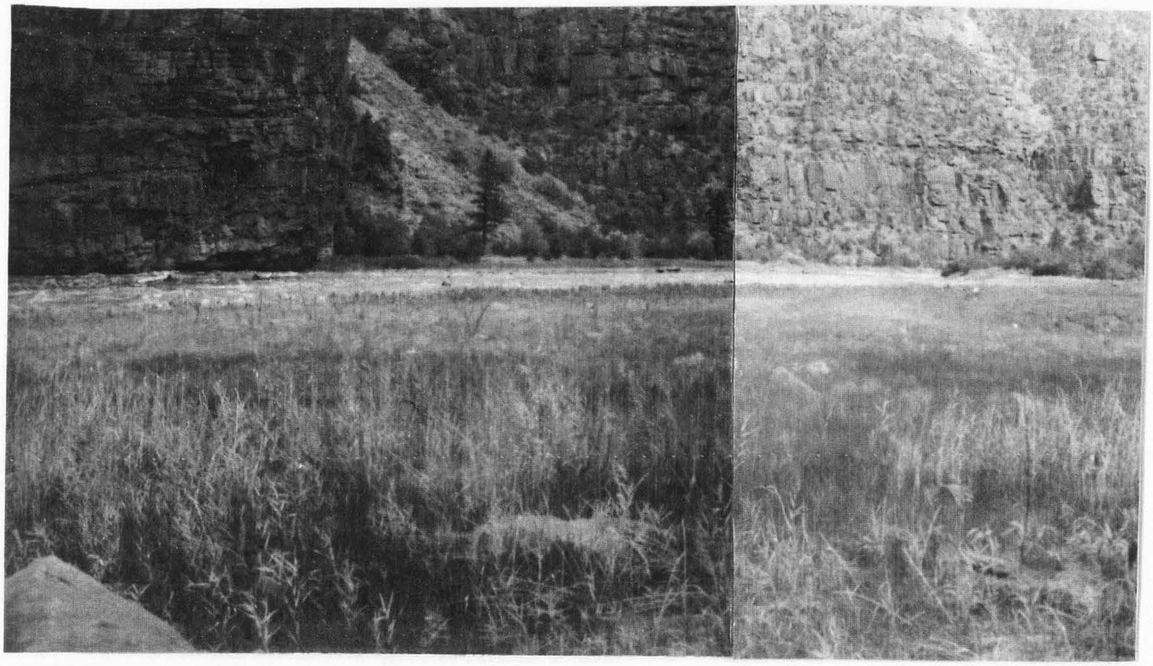


Figure 24. Topographic map and profile of the site shown in Figure 23. The shaded circle and arrow is the location and field of view of the photograph. In the plan view and profile, the active-channel deposits are shaded red, the post-dam flood plain is shaded green, the intermediate bench is shaded yellow, and the c-b terrace is shaded brown. The rock shown in Figure 23 is shaded black. The horizontal lines in the cross section show the elevation of the reattachment bar in 1871, estimated measurement in reference to the rock. The diagonal lines shade the outline of the former return-current channel, now filled. The inset relation of the intermediate bench to the c-b terrace is also shown. The detail is of an excavated tamarisk tree and shows germination ages of 1965 and 1973, indicating subsequent deposition that aggraded the intermediate bench to its present elevation.

a



b

Figure 25. Photograph taken on August 1, 1922 by Ralph Wooley on the U. S. Geological Survey expedition (a) looking across and upstream at Lower Disaster Falls in Lodore Canyon at Rkm 569.5. The match was taken September 26, 1996 (b). The entire area of exposed gravel shown in the 1922 photograph is now covered with a veneer of fine-grained sediment and vegetation. A portion of the bar on the right side of the photographs now has a thickness of up to 1.0 m of fine-grained sediment (Fig. 14).

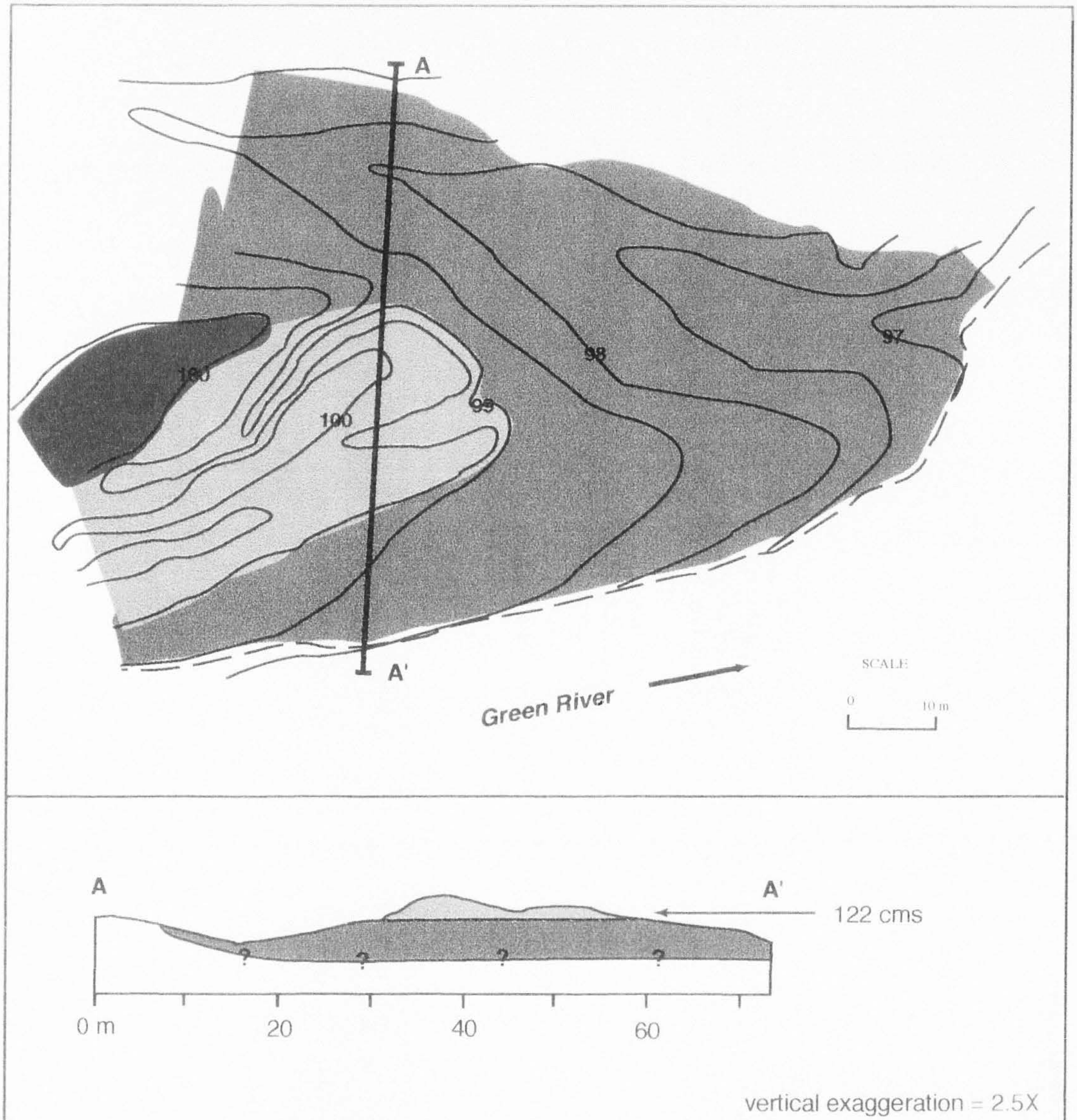
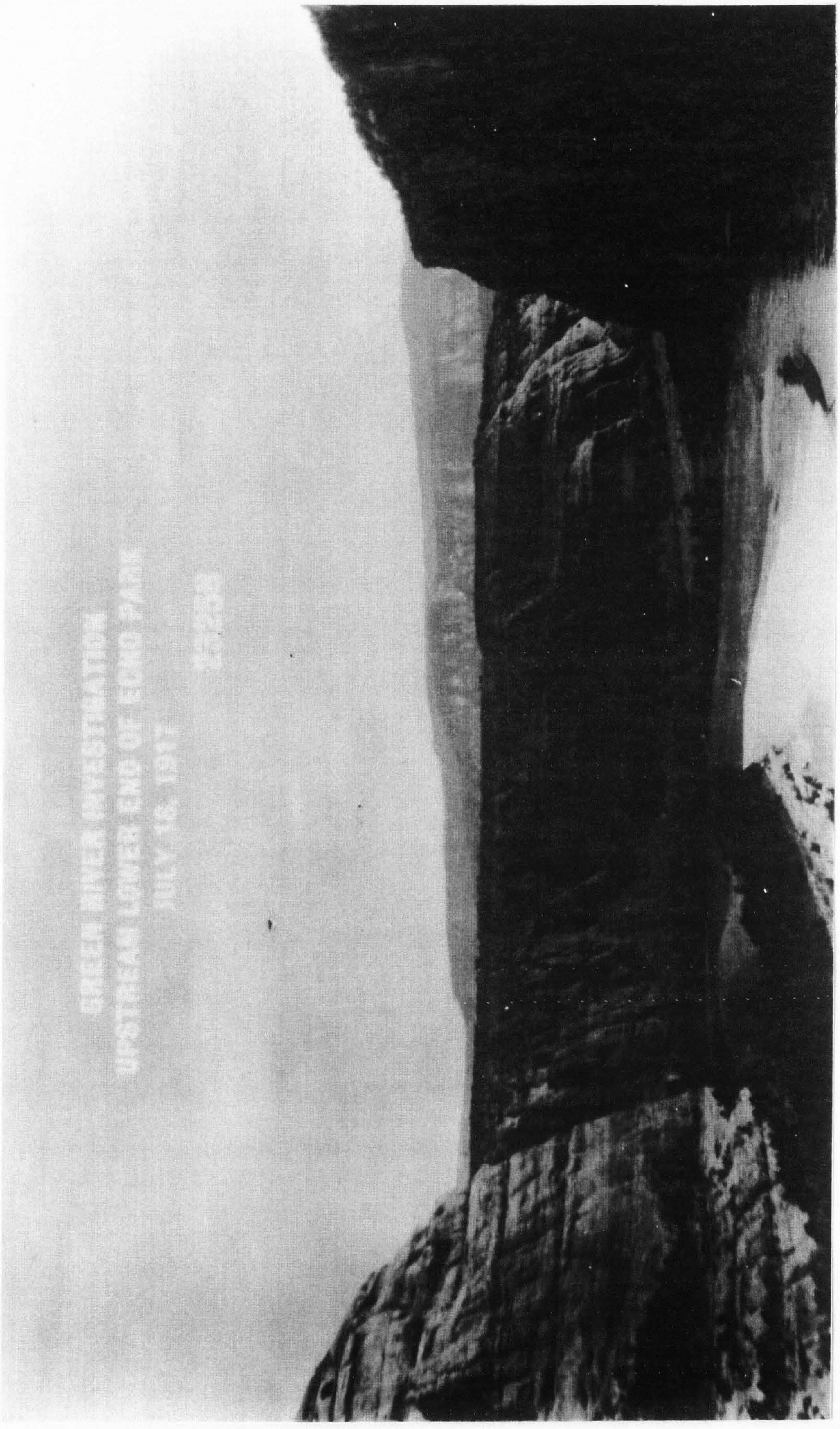


Figure 26. Topographic map and profile of the site shown in Figure 25. The post-dam flood plain is shaded green and is gravel covered by a veneer of fine-grained sediment, the depth of the gravel is not known as indicated by the question marks. The intermediate bench is shaded yellow and the profile shows the thickness of fine-grained sediment deposited on the gravel bar. The c-b terrace is shaded brown.

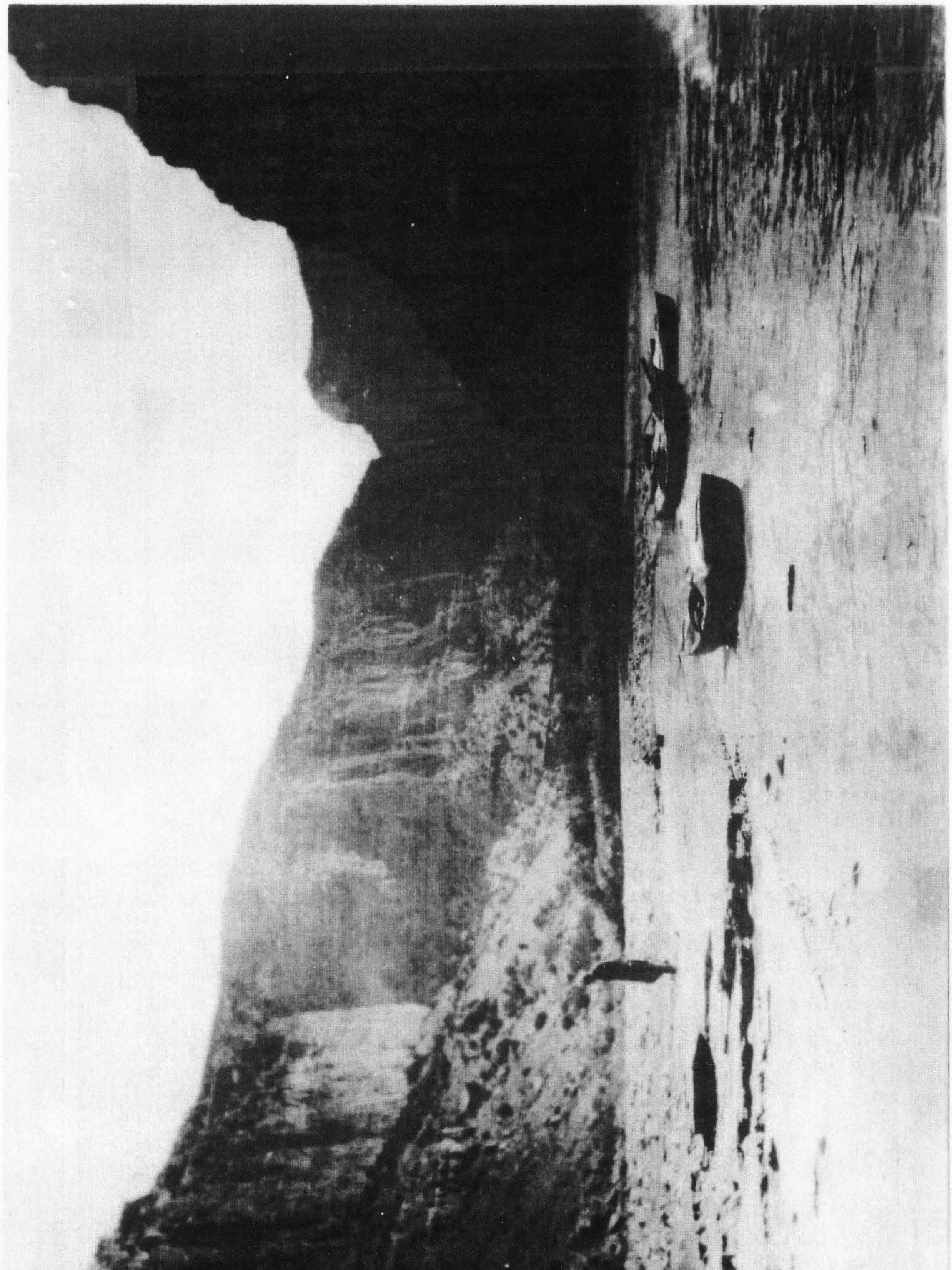
Figure 27. Photograph taken on July 18, 1917 by Ralph Wooley looking upstream in Echo Park from Rkm 548.5 (a) and match taken October 7, 1995 (b). The large active sand bar is about the same size now as it was in 1917. A large area of post-dam flood plain is now present in the 1917 active channel on river left upstream from the sand bar. The strip of c-b terrace in the foreground between the small hill and the sand bar is now much narrower than in 1917 showing erosion of this surface.


GREEN RIVER INVESTIGATION
UPSTREAM LOWER END OF ECHO PARK
JULY 16, 1917

a

b

Figure 28. Photograph taken September 25, 1909 by Raymond Cogswell of the Julius Stone expedition looking upstream in Whirlpool Canyon from the mouth of Jones Hole Creek at Rkm 540.7 (a). The match was taken September 28, 1996 (b). The present area of active gravel is still large. However, areas of fine-grained sediment deposition and vegetation establishment are visible in the foreground and on the left-hand side of the 1996 photograph.


a

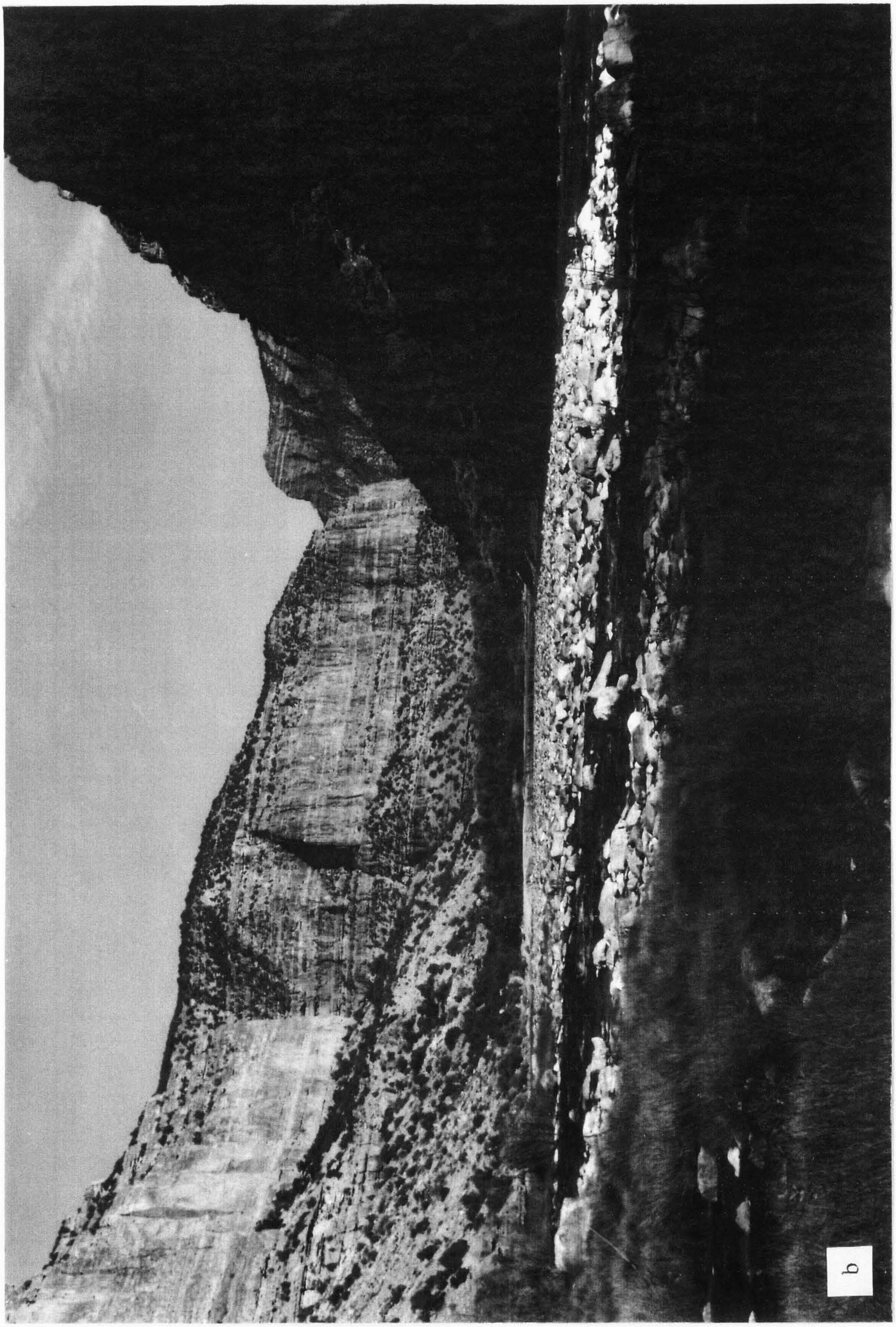
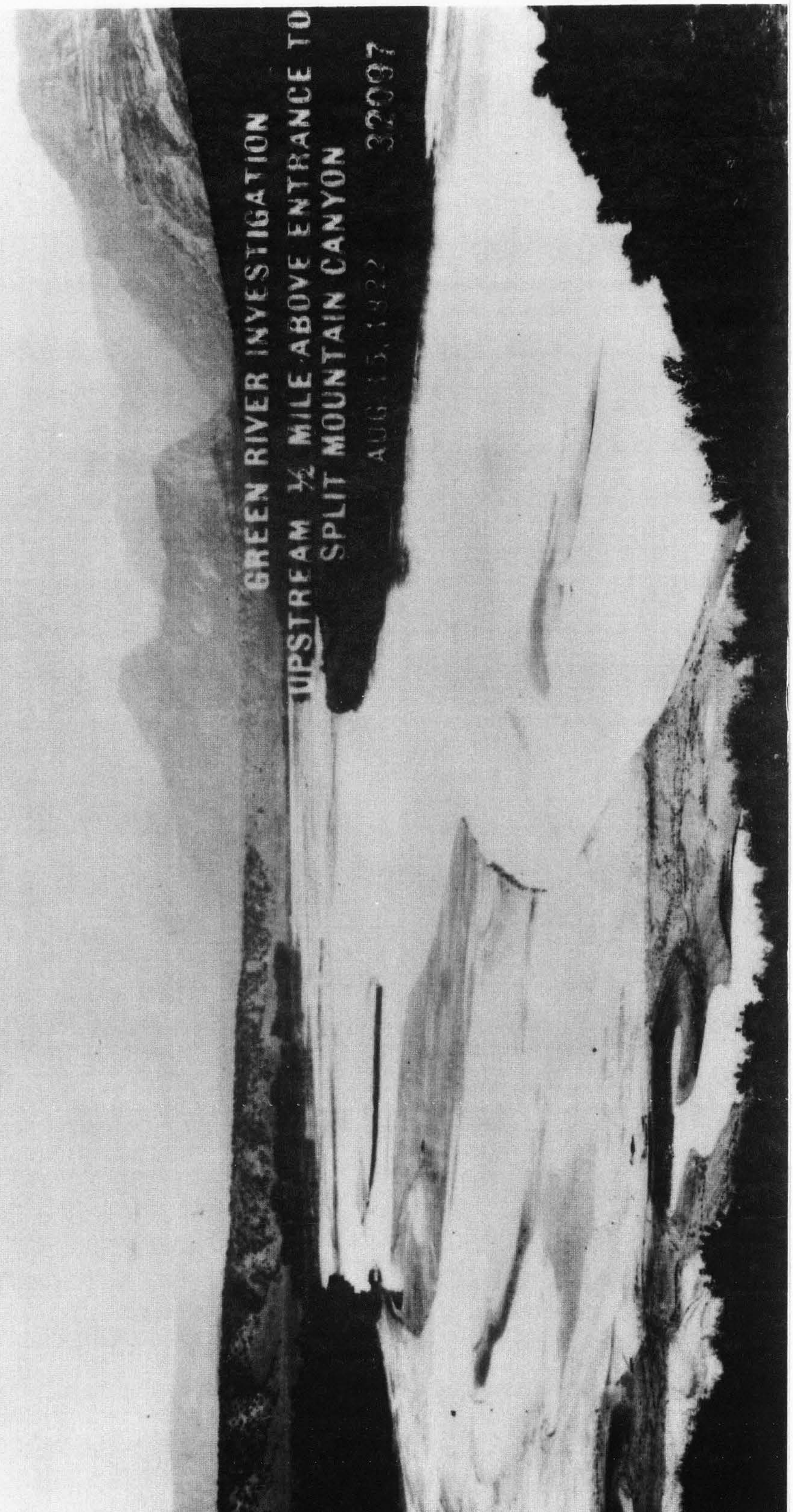
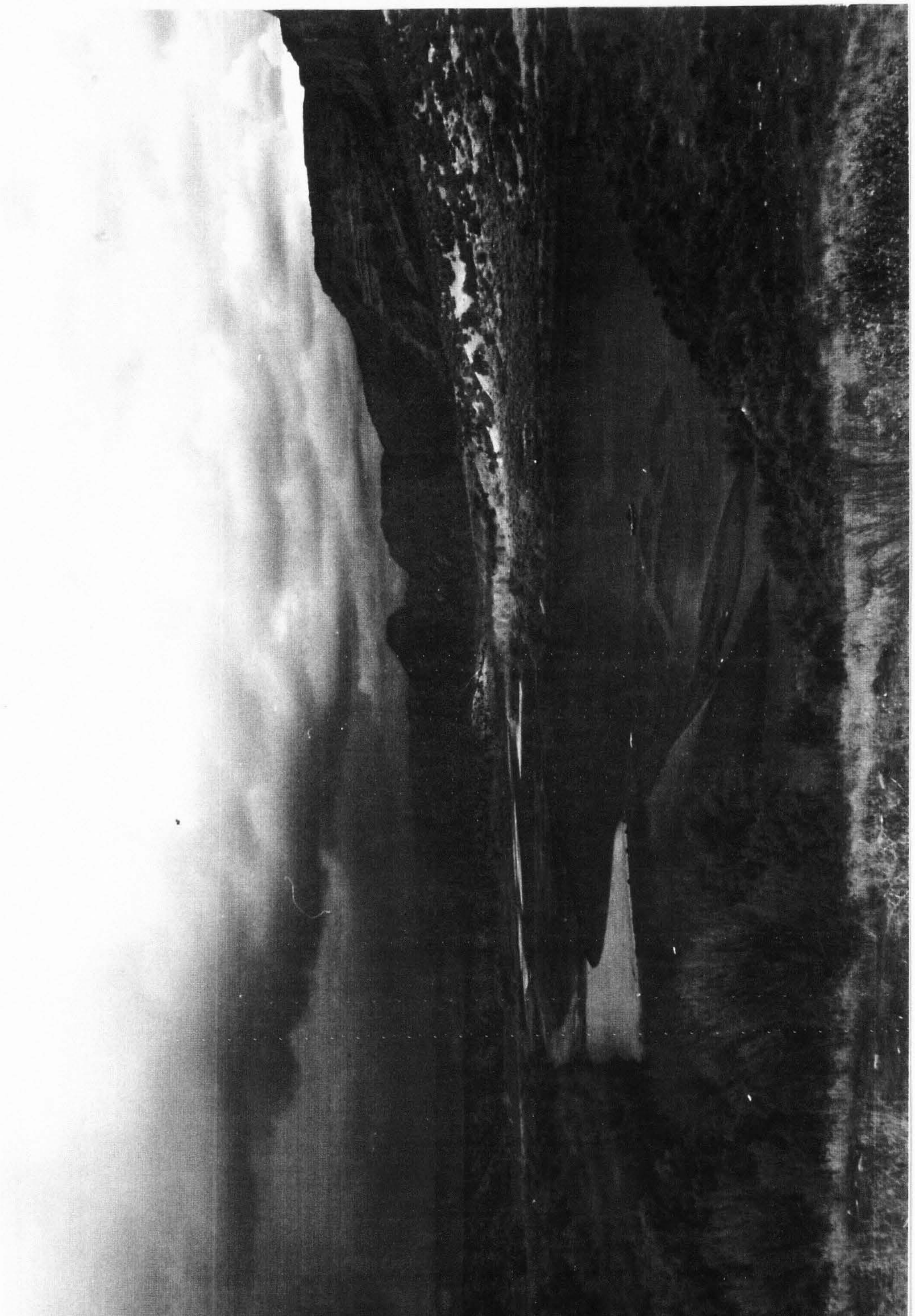

b

Figure 29. Photograph taken August 15, 1922 by Ralph Wooley on the U. S. Geological Survey expedition looking upstream in Island Park at Rkm 523.0 (a). The match was taken October 1, 1994 (b). The large open sand bar in the 1922 photograph is now much smaller and a deposit at the intermediate bench level now exists between the c-b terrace, far left, and the active-channel deposit. The deposit upstream from the sand bar on river right is a large area of post-dam flood plain that was active channel in 1922.


GREEN RIVER INVESTIGATION
UPSTREAM ½ MILE ABOVE ENTRANCE TO
SPLIT MOUNTAIN CANYON
32097

a



b

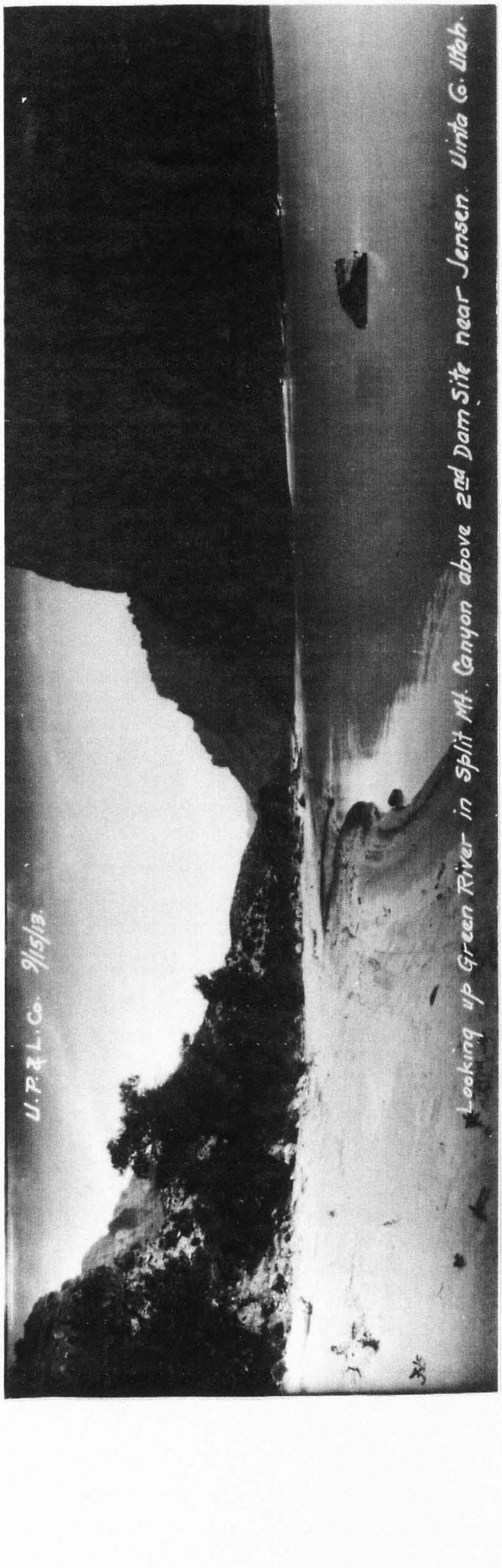
Figure 30. Photograph taken July 14, 1917 by Ralph Wooley looking down at Island Park from Ruple Point (a), the Green River is flowing from right to left. The match was taken October 8, 1995 (b). Several areas that were active channel in the 1917 photograph are now at the post-dam flood plain or intermediate bench level. The large c-b terrace island left and center in the 1917 photograph is now connected to the left bank and is a much smaller area of c-b terrace. The area of dense vegetation upstream from the c-b terrace in the 1995 photograph is now intermediate bench. This has occurred by deposition in the active channel and erosion of the c-b terrace.


GREEN RIVER INVESTIGATION
BIG BEND IN ISLAND PARK
JULY 14, 1917
23241

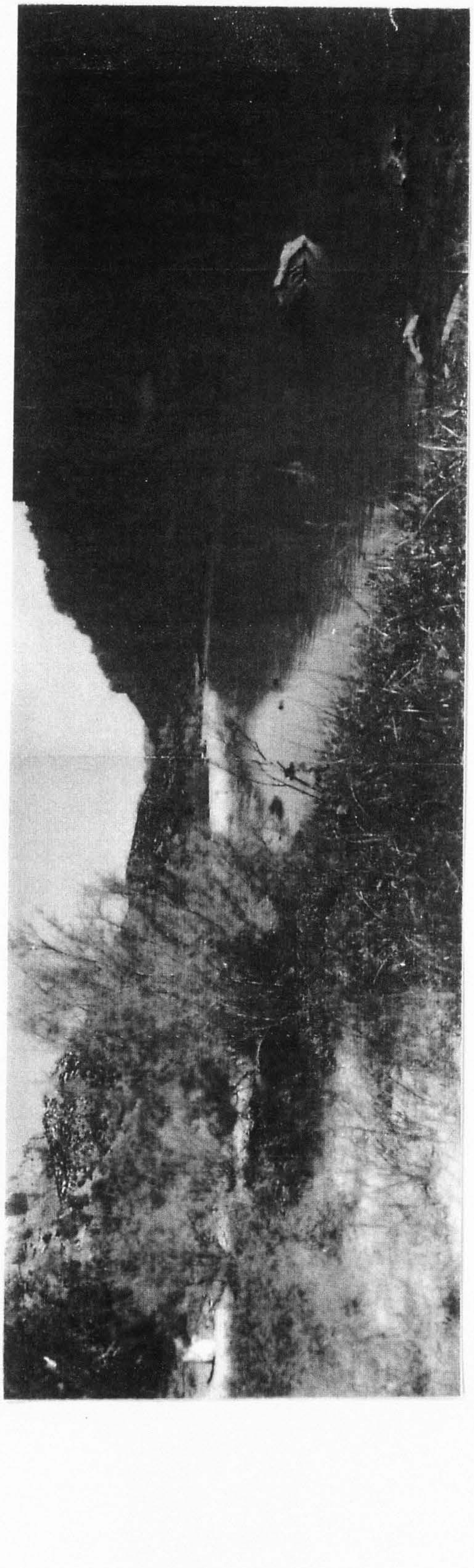
a

b

Figure 31. Photograph taken looking upstream in Split Mountain Canyon downstream from Inglesby Rapids at Rkm 512.7 on September 15, 1913 for a dam-location survey sponsored by the Utah Power and Light Company (a). The match was taken September 30, 1996 (b). The long, narrow sand bar deposited in an eddy and reworked by wave action is still present in 1996, but is narrower because much of the surface is covered with tamarisk trees and because it does not extend as far into the channel. The area in the foreground is the post-dam flood plain covered by grasses and tamarisk trees. The vegetation-covered surface left of the active sand bar in the center of the 1996 photograph is the intermediate bench. Most of the cottonwood trees present in the 1913 photograph are still present.


U.P.&L.Co. 9/15/13.
Looking up Green River in Split Mt. Canyon above 2nd Dam Site near Jensen. Uinta Co. Utah.

a



b

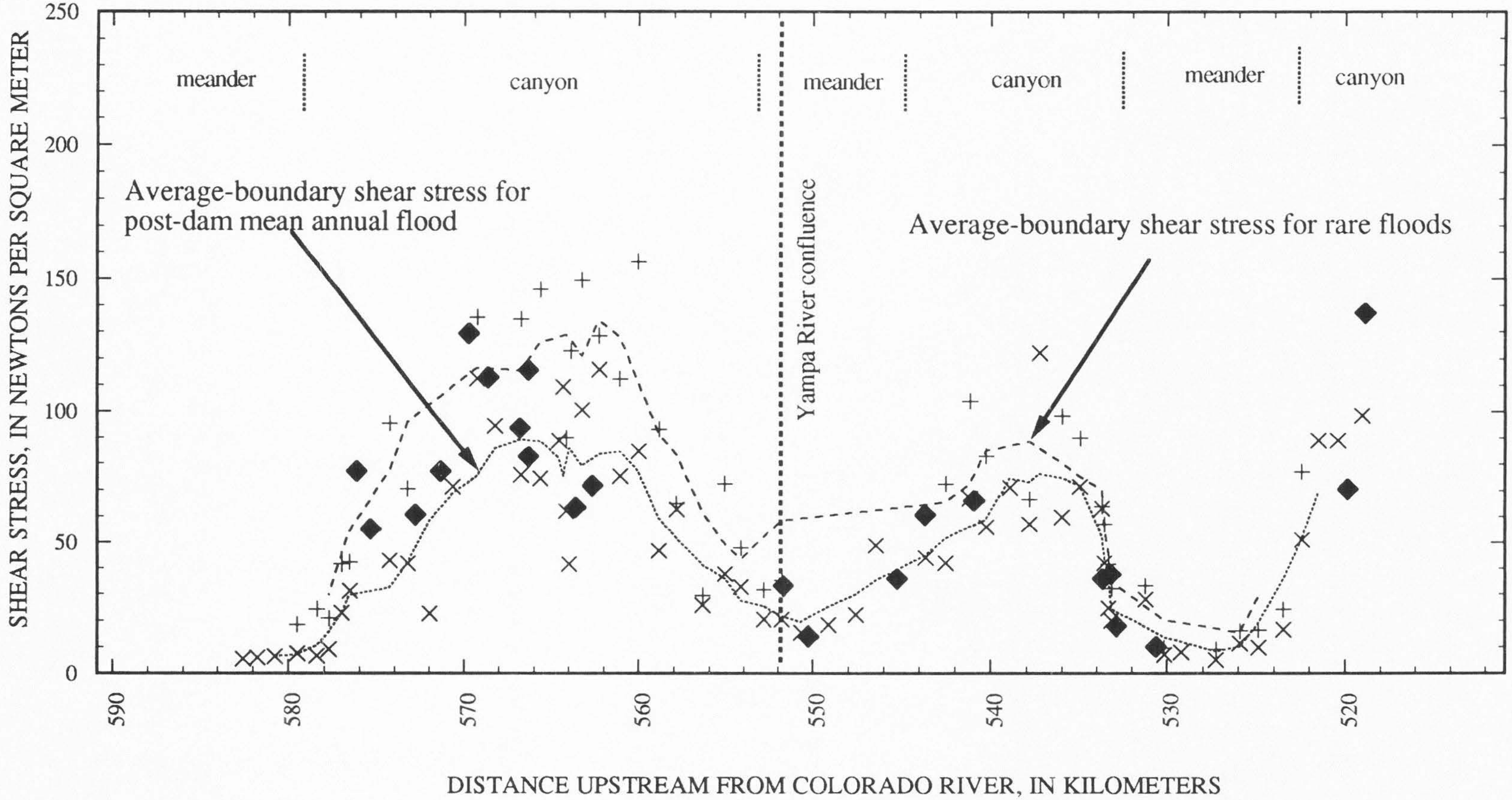


Figure 32. Estimated average boundary shear stress at cross sections and critical shear stress for gravel bars. Critical shear stress, shown by ◊'s, was calculated from the Shields function using 0.033 for the dimensionless critical shear stress. The +'s show average boundary shear stress for rare floods, the dashed line is a 5-point moving average. The x's show post-dam mean annual flood average boundary shear stress, the dotted line is a 5-point moving average. Comparison of the two curves shows that rare floods are required to mobilize the median diameter of gravel bars, particularly in canyon reaches. The mean annual flood mobilizes gravel in meandering reaches downstream from the Yampa River confluence.

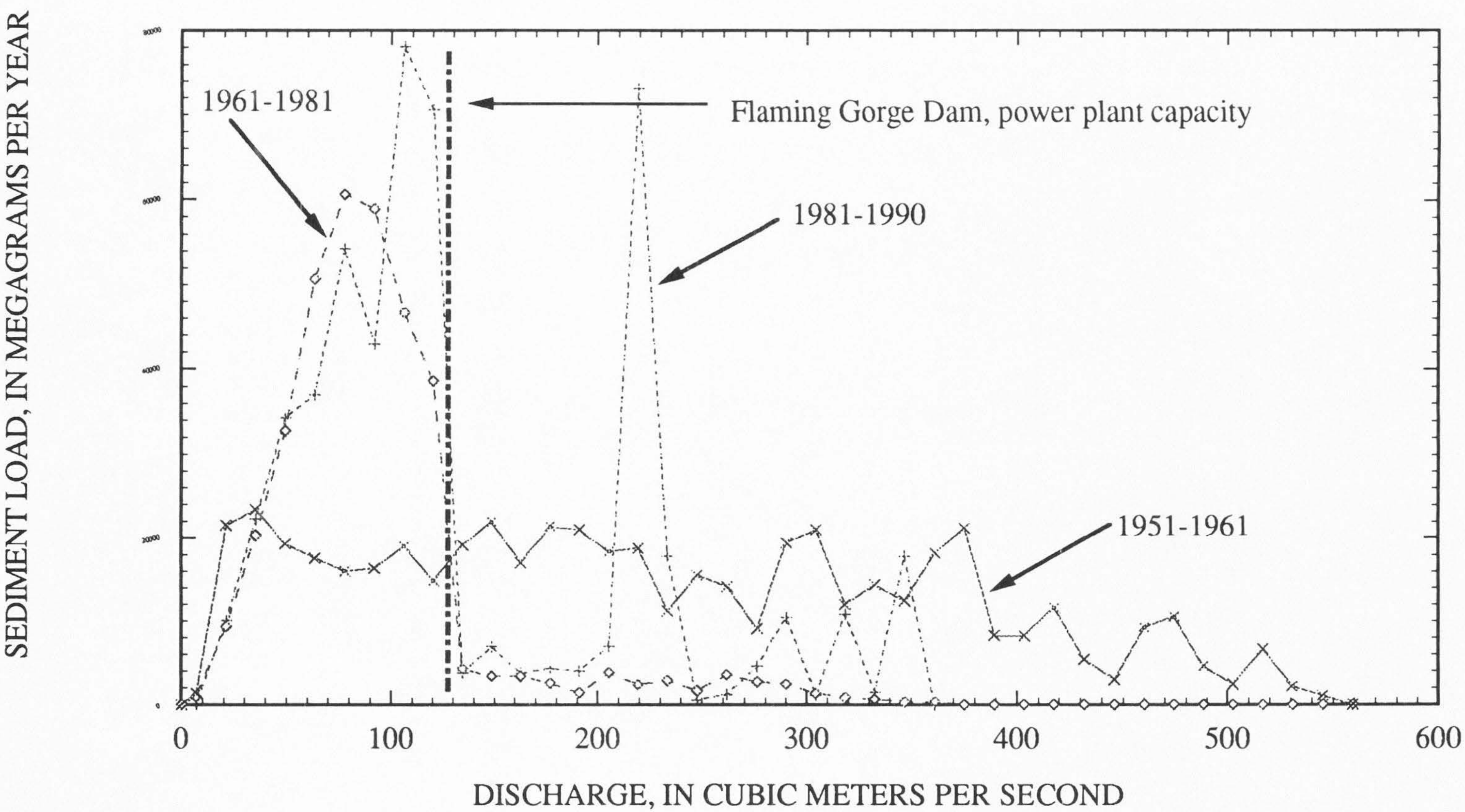


Figure 33. Product of sediment transport relation and daily-discharge duration curve estimated for the Green River at Gates of Lodore. Three time periods are shown: pre-dam is 1951 to 1961, post-dam without floods is 1961 to 1981, and post-dam with floods is 1981 to 1990.

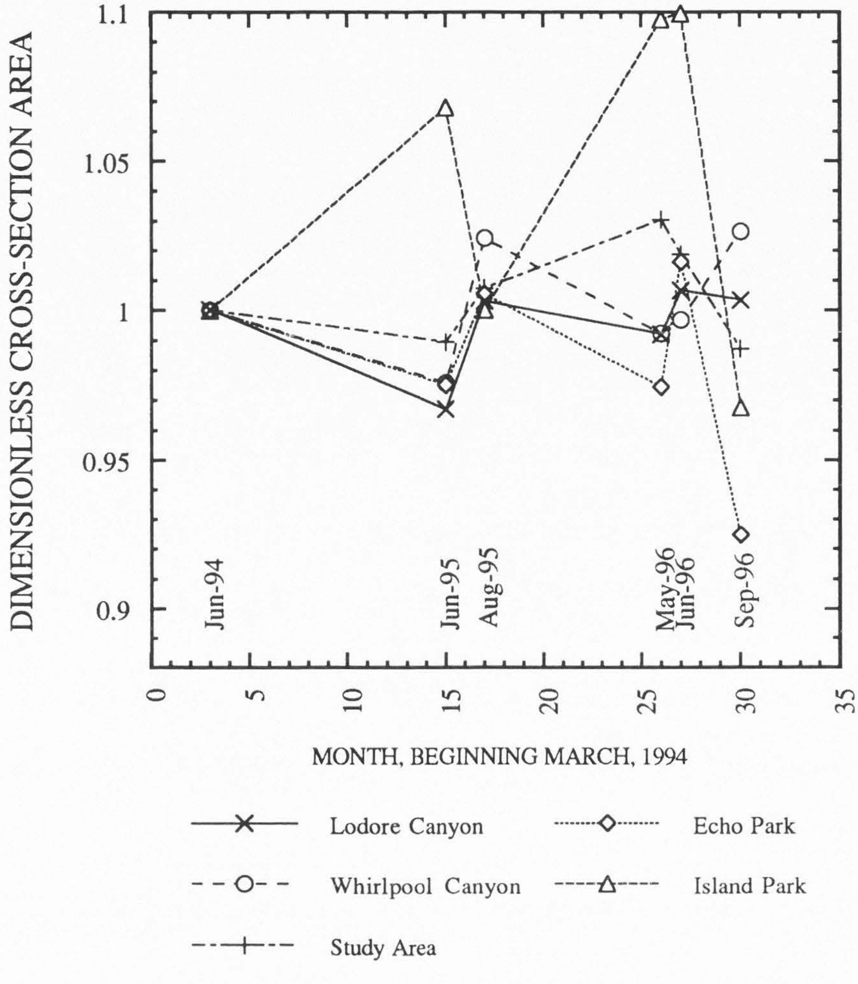


Figure 34. Average dimensionless cross-sectional area for indicated reaches between 1994 and September 1996. The area of each cross section was normalized by dividing the area by the area calculated for the first survey. Fill is shown by decrease in area and scour is shown by increase in area.

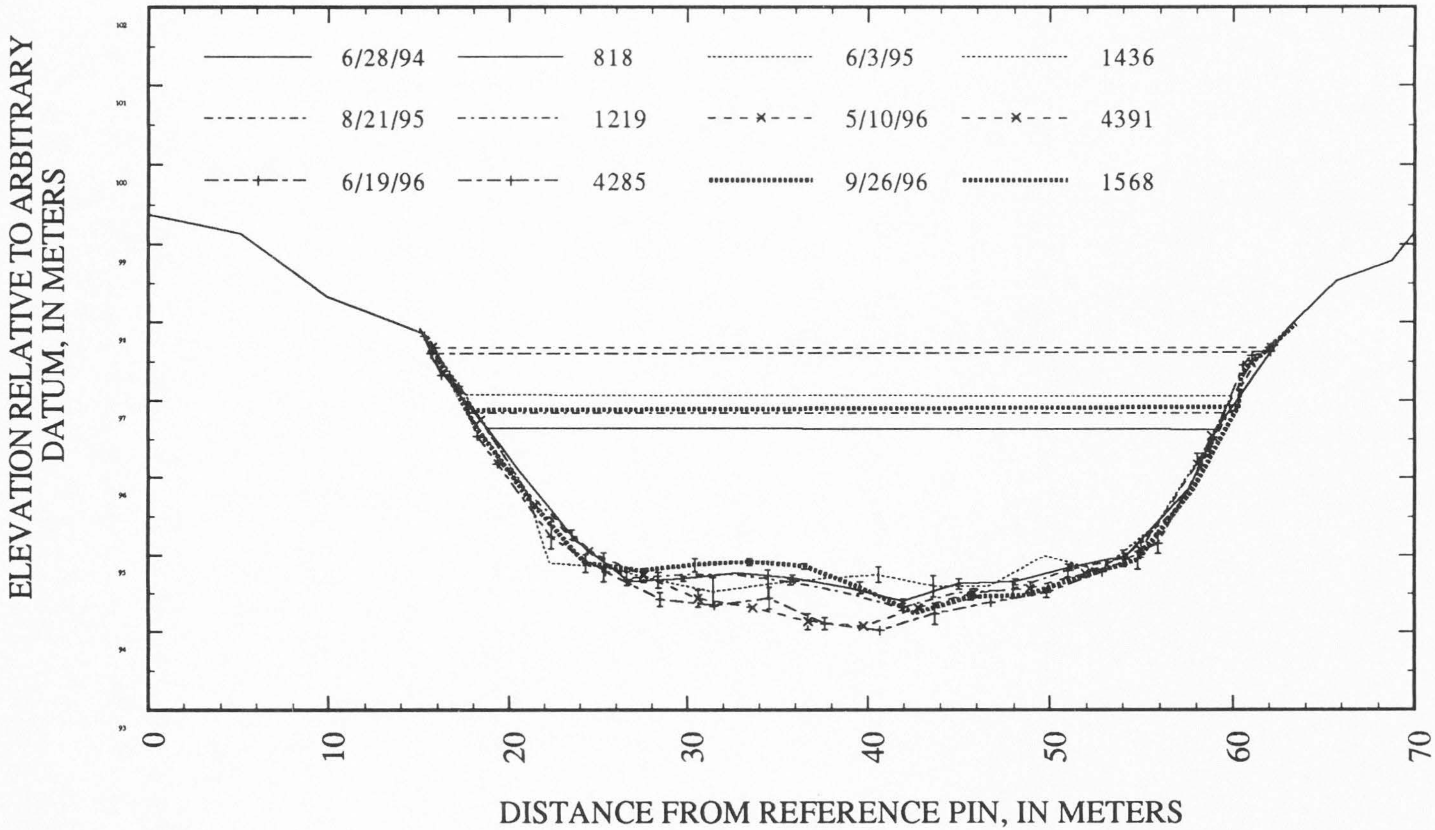


Figure 35. Channel cross section at Rkm 562.2 showing multiple surveys and scour-and-fill trend in Lodore Canyon. The error bars show the standard deviation determined from multiple fathometer passes. The final bed elevation is similar to the 1994 initial elevation which was nearly stable through August 21, 1995. A significant amount of scour occurred between August 21, 1995 and May 10, 1996. The cross-section was the same June 19, 1996 then filled to approximately its original elevation by September 26, 1996.

CHAPTER 4

CONCLUSION

The basic geomorphic characteristics of streams in canyons with debris fans are determined by the tributary sediment delivery processes. Longitudinal profile, channel geometry, and the occurrence of rapids in the canyons of the eastern Uinta Mountains are each strongly influenced by tributary-fan frequency. Bankfull channel width-to-depth ratio is lowest and gradient is steepest in the reaches with highest fan frequency, and all rapids are caused by debris fans or the gravel bars below debris fans composed of reworked debris fan material.

Expansion gravel bars are the other element of coarse-grained alluvial deposits in debris fan-dominated canyons. These bars are located in the expansion downstream from debris fan-created eddies where uniform downstream flow resumes. The lithology of gravels in these bars indicates that their source is the debris fan immediately upstream and its associated tributary basin. This is an indication that the process of local sorting outweighs downstream sorting in these canyons. Estimates of average boundary shear stress during floods and critical shear stress of gravel bars show that the channel gradient and bar-material size are in approximate adjustment with pre-dam flood conditions in both the canyon and meandering reaches of the study reach. Although the river flows alternately through reaches of extremely different geomorphic character, both are in a quasi-equilibrium condition.

Between 60 and 85 percent of the surface area of the alluvium in the canyon bottom exposed at low flow is contained in the depositional unit called the fan-eddy complex. More specifically, about 42 percent of all fine-grained alluvium in the canyons is stored in eddy bars within fan-eddy complexes. However, most of the total area of alluvium is contained in the meandering reaches where fan-eddy complexes are less important.

The fan-eddy complexes of the Green River in the eastern Uinta Mountains are similar to those described on the Colorado River in Grand Canyon by Schmidt and Rubin (1995). Approximately the same areal proportion of fine-grained alluvium is stored as eddy bars within these depositional units in both systems. In the eastern Uinta Mountains, however, there is less distinction between eddy-bar types; separation and reattachment bars are often merged.

Four distinct flood plain-like and terrace-like geomorphic features were mapped in the canyon and meandering reaches of the Green River and are (1) the cottonwood-box elder terrace, (2) the intermediate bench, (3) the post-dam flood plain, and (4) active channel deposits. The fine-grained component of these deposits is formed by vertical accretion, shown by examination of cutbank stratigraphy. The surface of each of these deposits occurs at a similar elevation above baseflow water surface and is thus inundated by similar discharges throughout the study area. This longitudinal correlation of flood plains and terraces distinguishes these features from the flood plains described by Nanson (1986) in other canyon rivers that were not longitudinally correlative. The c-b terrace is inundated only by rare pre-dam floods (> 25-yr return period). The intermediate bench is inundated by rare post-dam floods that are about equivalent to the pre-dam average flood. Finally, the post-dam flood plain is inundated by the post-dam average flood and active channel deposits are inundated even more frequently.

Historical photograph analysis indicates that the active channel of the Green River in the study reach has decreased in width by an average of 20 percent between pre-dam conditions and present. Pre-dam conditions were analyzed from photographs taken in 1871, 1917, 1922, 1938, and 1954. Channel narrowing occurred by formation of the intermediate bench and the post-dam flood plain geomorphic surfaces. In the canyon reaches, narrowing occurred in the channel-margin deposit, eddy bar, and expansion bar depositional facies. Channel narrowing in the expansion bar facies was manifest by the deposition of sand over gravel. Most of the channel narrowing in meandering reaches occurred in the mid-channel bar depositional facies and often involved filling-in of side channels and the attachment of islands to the river bank.

These results are also of interest to river managers who seek improved understanding of the relationship between dam operations and the condition of the downstream channel. Aggradation and stabilization of active channel deposits to form the intermediate bench and the post-dam flood plain have occurred, resulting in decreased areas of bare sand and gravel bars. Similar features in other reaches of the Green River provide habitat for endangered fish. The importance of this reduced habitat within the study area is not known. However, these new flood plain-like features provide habitat for riparian vegetation that supports a new terrestrial biological community.

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APPENDICES

APPENDIX A. LIST OF CROSS-SECTION LOCATIONS, DATES OF MEASUREMENT, AND DISCHARGE AT TIME OF MEASUREMENT

Cross-section number	Location, in Rkm	1994 Survey date	1994 Q*	Jun-95 Survey date	Jun-95 Q	Aug-95 Survey date	Aug-95 Q	May-96 Survey date	May-96 Q	Jun-96 Survey date	Jun-96 Q	Sep-96 Survey date	Sep-96 Q
1	585.43	22-Apr	41										
2	584.36	22-Apr	41	2-Jun	43	19-Aug	35	7-May	123	17-Jun	122		
3	583.49	23-Apr	42										
4	582.57	23-Apr	42	2-Jun	43	19-Aug	35	7-May	123				
5	581.73	23-Apr	42										
6	580.75	23-Apr	42	2-Jun	43	19-Aug	35	8-May	123	17-Jun	122	24-Sep	45
7	579.51	24-Apr	40					8-May	123				
8	578.40	24-Apr	40	3-Jun	41	19-Aug	35	8-May	123	17-Jun	122	25-Sep	45
9	577.72	22-Jun	24										
10	577.02	22-Jun	24	3-Jun	41	19-Aug	35	9-May	124	18-Jun	121	25-Sep	45
11	576.55	22-Jun	24										
12	575.58	28-Jun	23					9-May	124				
13	574.26	28-Jun	23	3-Jun	41	20-Aug	35	9-May	124	18-Jun	121	25-Sep	45
14	573.22	28-Jun	23										
15	571.95	28-Jun	23	3-Jun	41	20-Aug	35	9-May	124	18-Jun	121	25-Sep	45
16	570.63	29-Jun	23					9-May	124				
17	569.23	29-Jun	23	3-Jun	41	20-Aug	35						
18	568.21	29-Jun	23										
19	566.75	29-Jun	23	3-Jun	41	20-Aug	35	10-May	124	18-Jun	121		
20	565.64	30-Jun	27										
21	564.54	30-Jun	27	4-Jun	50	20-Aug	35	10-May	124	18-Jun	121	26-Sep	44
21.1	564.30	24-Aug						10-May	124	18-Jun	121		
21.2	564.14	24-Aug											
21.3	563.96	24-Aug						10-May	124	19-Jun	121	26-Sep	44
21.4	563.87	24-Aug											
22	563.24	30-Jun	27										

23	562.24	30-Jun	27	4-Jun	50	21-Aug	35	10-May	124	19-Jun	121	26-Sep	44
24	561.07	30-Jun	27										
25	560.01	1-Jul	27	4-Jun	50	21-Aug	35	10-May	124	19-Jun	121		
26	558.83	1-Jul	27					10-May	124				
27	557.83	1-Jul	27	4-Jun	50	21-Aug	35					27-Sep	44
28	556.35	1-Jul	27										
29	555.08	1-Jul	27	5-Jun	49	21-Aug	35	11-May	125	19-Jun	121	27-Sep	44
30	554.15	2-Jul	27					11-May	125				
31	552.84	2-Jul	27	5-Jun	49	21-Aug	35	11-May	125				
32	551.77	2-Jul	27					11-May	125				
33	550.67	10-Jul	39	5-Jun	479	22-Aug	59	11-May	455	19-Jun	326	27-Sep	54
34	549.14	10-Jul	39					11-May	455			27-Sep	54
35	547.57	10-Jul	39	5-Jun	479	22-Aug	59	11-May	455	20-Jun	318	28-Sep	55
36	546.46	11-Jul	39					12-May	459				
37	545.62	11-Jul	39			22-Aug	59	12-May	459			28-Sep	55
38	544.51	11-Jul	39										
39	543.62	11-Jul	39	6-Jun	490	23-Aug	59	12-May	459	20-Jun	318	28-Sep	55
40	542.50	12-Jul	38										
41	541.14	12-Jul	38	6-Jun	490	23-Aug	59						
42	540.24	12-Jul	38					12-May	459				
43	538.91	12-Jul	38	6-Jun	490	23-Aug	59	12-May	459			28-Sep	55
44	537.81	12-Jul	38										
45	537.25	28-Sep	47										
46	535.98	28-Sep	47	6-Jun	490	23-Aug	59						
47	534.96	28-Sep	47										
48.1	533.69	17-Nov											
48.2	533.56	17-Nov		6-Jun	490	24-Aug	59	12-May	459				
48.3	533.32	17-Nov											
48.4	533.16	17-Nov											
49	532.04	29-Sep	47										

50	531.23	29-Sep	47	6-Jun	490	24-Aug	59	13-May	451	20-Jun	318	29-Sep	56
51	530.15	29-Sep	47										
52	529.19	29-Sep	47	7-Jun	520	24-Aug	59	13-May	451			29-Sep	56
53	527.24	30-Sep	47					13-May	451				
54	525.89	30-Sep	47	7-Jun	520	24-Aug	59	13-May	451	20-Jun	318	29-Sep	56
55	524.86	1-Oct	47										
56	523.46	1-Oct	47					14-May	482				
57	522.41	2-Oct	47					14-May	482			29-Sep	56
58	521.49	2-Oct	47					14-May	482				
59	520.40	2-Oct	47										
60	519.05	2-Oct	47										

* Discharge at time of cross-section survey, in cubic meters per second.

APPENDIX B. LIST OF HISTORICAL PHOTOGRAPHS REPLICATED, SOURCE OF PHOTOGRAPH, AND DATES OF PHOTOGRAPHY

Date of original	Date of match	Photographer*	Index Number	Location Rkm†		Reach	Source of Photograph
1872	8/19/95	T. O'Sullivan	n	579.8	L	Lodore Can.	
1872	8/19/95	T. O'Sullivan	38	579.8	L	Lodore Can.	National Archives
6/17/1871	8/21/93	E.O. Beaman	473	579.8	L	Lodore Can.	National Archives
9/21/09	8/19/95	R. Cogswell	85	579.8	L	Lodore Can.	Bancroft Library, University of California
7/31/22	8/19/95	R.R. Wooley	32008	579.4	R	Lodore Can.	National Archives
7/29/17	4/24/94	R.R. Wooley	23416	579.4	L	Brown's Park	National Archives
6/17/1871	8/22/93	E.O. Beaman	428	577.6	R	Lodore Can.	National Archives
6/17/1871	8/21/93	E.O. Beaman	504	577.6	R	Lodore Can.	National Archives
1872	5/15/96	T. O'Sullivan	40	577.6	L	Lodore Can.	National Archives
1872	5/15/96	T. O'Sullivan	64	577.6	L	Lodore Can.	National Archives
6/17/1871	8/22/93	E.O. Beaman	503	577.1	R	Lodore Can.	National Archives
1872	9/17/94	T. O'Sullivan	20	573.4	L	Lodore Can.	National Archives
9/21/09	8/20/95	R. Cogswell	95	572.0	R	Lodore Can.	Bancroft Library, University of California
9/21/09	7/3/95	R. Cogswell	96	571.6	R	Lodore Can.	Bancroft Library, University of California
6/18/1871	8/22/93	E.O. Beaman	571	570.4	R	Lodore Can.	National Archives
6/18/1871	8/22/93	E.O. Beaman	577	570.4	R	Lodore Can.	National Archives
6/19/1871	8/23/93	E.O. Beaman	581	570.2	L	Lodore Can.	National Archives
9/22/09	8/20/95	R. Cogswell	100	570.0	L	Lodore Can.	Bancroft Library, University of California
8/1/22	8/23/93	R.R. Wooley	32030	569.5	L	Lodore Can.	Special Collections, University of Utah
6/21/1871	8/24/93	E.O. Beaman	590	566.7	R	Lodore Can.	National Archives
6/21/1871	8/24/93	E.O. Beaman	584	566.5	R	Lodore Can.	National Archives
8/3/22	8/26/94	R.R. Wooley	32044	563.9	L	Lodore Can.	Special Collections, University of Utah
8/3/22	8/26/94	R.R. Wooley	32045	563.9	L	Lodore Can.	Special Collections, University of Utah
9/23/09	8/21/95	R. Cogswell	113	563.3	L	Lodore Can.	Bancroft Library, University of California
6/21/1871	8/24/93	E.O. Beaman	604	563.0	R	Lodore Can.	National Archives
6/21/1871	8/24/93	E.O. Beaman	610	563.0	R	Lodore Can.	National Archives
6/22/1871	8/25/93	E.O. Beaman	601	562.8	L	Lodore Can.	National Archives
6/22/1871	8/25/93	E.O. Beaman	628	562.8	L	Lodore Can.	National Archives
8/3/22	8/21/95	R.R. Wooley	32050	562.6	L	Lodore Can.	Special Collections, University of Utah
8/3/22	8/21/95	R.R. Wooley	32058	559.9	R	Lodore Can.	Special Collections, University of Utah
9/24/09	8/22/95	R. Cogswell	140	555.1	R	Lodore Can.	Bancroft Library, University of California
1872	10/24/94	T. O'Sullivan	42	555.1	L	Lodore Can.	National Archives
7/1/1871	8/22/95	E.O. Beaman	600	551.4	L	Echo Park	National Archives
9/24/09	10/25/94	R. Cogswell	148	550.2	L	Echo Park	Bancroft Library, University of California
7/18/17	10/7/95	R.R. Wooley	23258	548.6	L	Echo Park	Special Collections, University of Utah
9/24/09	10/23/94	R. Cogswell	151	548.5	R	Echo Park	Bancroft Library, University of California
9/25/09	9/28/96	R. Cogswell	161	540.9	R	Whirlpool Can.	Bancroft Library, University of California
9/26/13	8/23/95	F. L. Hess	549	538.3	R	Whirlpool Can.	U.S.G.S.
8/9/22	8/26/93	R.R. Wooley	32028	533.5	R	Island Park	Special Collections, University of Utah
9/25/09	8/23/95	R. Cogswell	170	533.3	R	Island Park	Bancroft Library, University of California
?	8/23/95	U.S.G.S.	57	533.3	R	Island Park	Special Collections, University of Utah
7/6/1871	8/26/93	E.O. Beaman	681	533.2	L	Island Park	National Archives
8/10/22	9/29/94	R.R. Wooley	32087	532.4	R	Island Park	Special Collections, University of Utah
7/14/17	10/8/95	R.R. Wooley	23241	526.9	L	Island Park	Special Collections, University of Utah
8/15/22	10/1/94	R.R. Wooley	32097	523.0	R	Island Park	Special Collections, University of Utah
8/15/22	8/27/93	R.R. Wooley	32098	523.0	R	Island Park	Special Collections, University of Utah
9/26/09	8/24/95	R. Cogswell	183	520.5	L	Split Mtn. Can.	Bancroft Library, University of California
7/10/1871	8/27/93	E.O. Beaman	694	518.5	R	Split Mtn. Can.	National Archives
9/26/09	8/24/95	R. Cogswell	188	516.9	R	Split Mtn. Can.	Bancroft Library, University of California
9/15/13	8/24/95	U.S.G.S.	63	516.4	L	Split Mtn. Can.	Special Collections, University of Utah
8/18/22	8/25/95	R.R. Wooley	32112	513.1	R	Split Mtn. Can.	Special Collections, University of Utah
8/18/22	8/25/95	R.R. Wooley	32114	511.6	L	Split Mtn. Can.	Special Collections, University of Utah
8/18/22	11/20/93	R.R. Wooley	32117	510.5	L	Split Mtn. Can.	Special Collections, University of Utah
8/18/22	11/20/93	R.R. Wooley	32118	510.5	L	Split Mtn. Can.	Special Collections, University of Utah
7/12/17	11/20/93	R.R. Wooley	23226	510.0	L	Split Mtn. Can.	Special Collections, University of Utah
9/15/13	9/30/96	U.S.G.S.	3810	512.7	R	Split Mtn. Can.	Special Collections, University of Utah

* T. O'Sullivan was the photographer on the 1872 Clarence King expedition, E.O. Beaman was the photographer on the 1871 John Wesley Powell Expedition, R. Cogswell was the photographer on the 1909 Julius Stone expedition, R. R. Wooley was the photographer for U.S. Geological Survey/Utah Power and Light Expeditions. The photographer for some U.S. Geological Survey expeditions is unknown.

† Location in km upstream from Colorado River confluence, and side of river when looking downstream.

APPENDIX C. TABULATION OF HISTORICAL PHOTOGRAPH DATA

Photographer	Number	Rkm	Reach	Increase in vegetation	New sand over gravel	Evidence for channel narrowing	Erosion of high terrace	No change	Subject of photograph
T. O'Sullivan	n	579.8	Lodore Can.	X		X			channel margin
T. O'Sullivan	38	579.8	Lodore Can.	X		X			channel margin
E.O. Beaman	473	579.8	Lodore Can.					X	channel margin
Stone	85	579.8	Lodore Can.	X		X			channel margin
R. Wooley	32008	579.4	Lodore Can.	X		X			channel margin
E.O. Beaman	428	577.6	Lodore Can.	X		X			eddy bar
E.O. Beaman	504	577.6	Lodore Can.	X		X			eddy bar
T. O'Sullivan	40	577.6	Lodore Can.	X					channel margin
T. O'Sullivan	64	577.6	Lodore Can.	X					channel margin
E.O. Beaman	503	577.1	Lodore Can.	X	X	X			channel margin
T. O'Sullivan	20	573.4	Lodore Can.	X		X			channel margin
Stone	95	572.0	Lodore Can.	X	X	X			gravel bar
Stone	96	571.6	Lodore Can.	X		X			channel margin
E.O. Beaman	571	570.4	Lodore Can.					X	debris fan
E.O. Beaman	575	570.4	Lodore Can.					X	debris fan
E.O. Beaman	577	570.4	Lodore Can.					X	debris fan
E.O. Beaman	581	570.2	Lodore Can.	X					debris fan
Stone	100	570.0	Lodore Can.	X	X				gravel bar
R. Wooley	32030	569.5	Lodore Can.	X	X	X			gravel bar
E.O. Beaman	590	566.7	Lodore Can.	X		X			channel margin
E.O. Beaman	584	566.5	Lodore Can.	X					debris fan
R. Wooley	32044	563.9	Lodore Can.	X		X			eddy bar
R. Wooley	32045	563.9	Lodore Can.	X		X			eddy bar
Stone	113	563.3	Lodore Can.	X		X			channel margin
E.O. Beaman	604	563.0	Lodore Can.					X	rapid
E.O. Beaman	610	563.0	Lodore Can.	X					rapid
E.O. Beaman	601	562.8	Lodore Can.	X					rapid
E.O. Beaman	628	562.8	Lodore Can.	X				X	debris fan
R. Wooley	32050	562.6	Lodore Can.	X		X			gravel bar
R. Wooley	32058	559.9	Lodore Can.	X	X	X			gravel bar
Stone	140	555.1	Lodore Can.	X		X			channel margin
T. O'Sullivan	42	555.1	Lodore Can.	X					channel margin
E.O. Beaman	600	551.4	Echo Park	X		X	X		bar, terrace
Stone	148	550.2	Echo Park	X					channel margin
R. Wooley	23258	548.6	Echo Park	X		X	X		bar, terrace
Stone	151	548.5	Echo Park	X			X		bar, terrace
Stone	161	540.7	Whirlpool Can.	X		X			gravel bar
F. L. Hess	549	538.3	Whirlpool Can.	X					gravel bar
R. Wooley	32028	533.5	Island Park	X	X	X			mid-channel bar
Stone	170	533.3	Island Park	X	X				mid-channel bar
R. Wooley	57	533.3	Island Park	X	X				gravel bar
E.O. Beaman	681	533.2	Island Park	X			X		mid-channel bar
R. Wooley	32087	532.4	Island Park	X		X			mid-channel bar
R. Wooley	23241	526.9	Island Park	X		X	X		mid-channel bar
R. Wooley	32097	523.0	Island Park	X		X			channel margin
R. Wooley	32098	523.0	Island Park	X		X			channel margin
Stone	183	520.5	Split Mtn. Can.	X					gravel bar
E.O. Beaman	694	518.5	Split Mtn. Can.					X	gravel bar
E.O. Beaman	698	518.5	Split Mtn. Can.					X	gravel bar
E.O. Beaman	690	518.5	Split Mtn. Can.					X	gravel bar
Stone	188	516.9	Split Mtn. Can.	X					gravel bar
R. Wooley	63	516.4	Split Mtn. Can.	X		X			eddy bar
R. Wooley	3810	512.7	Split Mtn. Can.	X		X			eddy bar
R. Wooley	32112	513.1	Split Mtn. Can.	X					debris fan
R. Wooley	32114	511.6	Split Mtn. Can.	X					gravel bar
R. Wooley	32117	510.5	Split Mtn. Can.	X		X			channel margin
R. Wooley	32118	510.5	Split Mtn. Can.	X		X			channel margin

APPENDIX D. AREA OF EACH CROSS SECTION FOR EACH MEASUREMENT DATE

Cross-section number	1994*	Jun-95†	Aug-95	May-96	Jun-96	Sep-96
6	1.00		1.04	1.16	1.09	1.07
7	1.00			0.87		
8	1.00	0.92	1.09	0.90	0.95	1.07
10	1.00	1.00	1.00	0.94	0.98	0.89
13	1.00	1.00	1.01	1.00	0.98	0.99
15	1.00	0.94	1.03	0.97	0.96	1.02
17	1.00	0.93	0.94			
19	1.00	0.96	1.01	1.02	0.98	
21	1.00	1.01	1.01	1.04	1.00	1.03
21.1	1.00			1.02	1.03	
23	1.00	1.00	1.02	1.04	1.09	1.02
25	1.00	1.04	0.98	0.95	1.03	
27	1.00			1.02		0.92
29	1.00	0.85	0.97	0.89	0.97	1.04
30	1.00			1.08		
31	1.00	0.99	0.94	1.04		
32	1.00			0.94		
33	1.00	0.91	1.07	0.98	1.02	1.02
34	1.00			0.94		0.86
35	1.00	1.04	0.94	1.00	1.02	0.89
37	1.00		1.04	1.01		1.07
39	1.00	0.98	0.97	0.98	1.00	1.01
41	1.00	0.99	1.01			
42	1.00			1.01		
43	1.00	0.96	1.01	0.96		1.00
46	1.00		1.08			
48.2		0.96	1.02	0.97		
50	1.00	0.91	0.97	1.34	0.99	1.01
52	1.00	1.20	1.00	1.20		0.97
53	1.00			0.94		
54	1.00	1.21	1.01	1.18	1.21	0.94
56	1.00			1.02		
57	1.00			1.04		0.96
58	1.00			1.50		

* The area for each measurement is normalized to the area for the first measurement.

† Refer to Appendix A for the exact date of measurement.